MASTER THESIS

Implementation Planning of Sustainable Digital Twins in Modular Construction

A FRAMEWORK FOR DERIVING STRATEGIC RECOMMENDATIONS

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Preface

This report is the result of a master thesis project looking into the implementation planning of sustainable digital twins for modular construction, and the development of a framework to derive strategic recommendations. It also concludes my master study program in Civil Engineering and Management at the University of Twente. This research was conducted in cooperation with the University of Twente, and the modular construction company geWOONhout.

The thesis develops a framework to design a digital twin structure that helps a company with the digital twin implementation. Next to that it also looks into sustainable digital twin uses for a modular construction company, and shows how to implement the framework through a case study.

This study was only possible through the great cooperation and support of my supervisors at geWOONhout, and the advice from my supervisors at the University of Twente. Thus, I would like to thank Arjen Adriaanse and Irfan Pottachola for their feedback and support throughout the development of this thesis. Their advice was crucial to structure my ideas and communicate them. Further, I would like to thank Linda Braakman, who was a great help in navigating the business side of this research, finding my information sources, and integrating research and company interests.

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Summary

The issue of sustainability is an increasingly important topic in the construction industry, especially as the yearly emissions from construction and building operation reach an all-time high. Among other solutions, increasing the digitalization especially related to digital twins has been suggested to increase the efficiency and sustainability of construction processes. Digital twins are cyber-physical systems, that analyze (real-time) data to plan and implement interventions for their physical counterpart. However, while other industries have already developed digital twins for their purposes, this aspect of digital technology has yet to become standard in the construction industry. One hindrance to their implementation is a lack of practical understanding regarding their design and implementation, especially in connection to environmental sustainability. Thus, this research assessed the use of sustainable digital twin applications for a modular construction company, and developed a framework to plan their implementation.

First, this research developed a theoretical digital twin framework that focused on identifying the elements of a digital twin. This framework is a digital twin element architecture (DTEA), which divides the digital twin into 25 elements throughout seven layers that are defined through a series of questions specific to each element. Additionally, a gap analysis is proposed for the development of strategic recommendations the implementation of a specific digital twin application in a company, which is based on the DTEA.

This framework was then verified and validated through a case study with a modular construction company. For this case study, two specific sustainable digital twin applications needed to be selected. It was considered important that they represented the priorities of the company, thus nine potential digital twin applications were selected based on the sustainability goals, the related processes, and the interests of the company. These potential DT uses include (1) building energy benchmarking, (2) automated multi-parameter design optimization, (3) automated sustainability rating scheme, (4) BIM-based LCA, (5) BIM-based BCA, (6) automatic material passport generation, (7) calibrated building energy simulation, (8) assembly equipment energy management, and (9) sustainable indoor environmental quality optimization. The nine potential applications were then reviewed to determine their benefits and resource needs, and then evaluated by the company to select the most suitable ones for the case study. Accordingly, building energy benchmarking and BIM-based life cycle assessment were selected as the most suitable applications for the case study.

The case study designed DTEAs for the digital twin applications, and derived strategic recommendations for their implementation. These were then evaluated by the company, which affirmed that they gained an overview of the elements of a DT for each application, that it could assist them in reaching their sustainability goals, that it considered their priorities, and that the results could assist their implementation implementation.

Next to the development of the framework itself, the study identified further aspects important for the development of a digital twin. For one, the amount of guidance provided through the separation in different elements with guiding questions was highlighted as beneficial for the practical application. Further, it was remarked that the strategic recommendations could provide guidance, yet more detailed recommendations would be necessary to plan the specific implementation. Yet, it was also noted that for this level of detail an interdisciplinary approach to developing the DTEA would be more appropriate. Additionally, it was determined that stakeholders are an important aspect to consider when planning a digital twin, and that estimating the value a digital twin provides is important for marketing its implementation to companies and other stakeholders.

Finally, this research also identified further research gaps that need to be addressed in future research. In the future especially the maintenance of digital twins, the process of interdisciplinary digital twin design, and the value provided by digital twins should be assessed. Lastly, this research only conducted a theoretical validation of the framework, future research needs to validate its use for practical implementations.

Glossary

AECO-FM	Architecture, Engineering, Construction, Operation, and Facility Management
API	Application Programming Interface
ASCE	American Society of Civil Engineers
BCA	Building Circularity Assessment
BENG	Nearly Energy Neutral Building (NL: Bijna Energieneutrale Gebouwen)
BIM	Building Information Modelling
BoQ	Bill of Quantities
BTIC	Construction Technology and Innovation Centre (NL: Bouw en Techniek Innovatiecentrum)
CO_2	Carbon Dioxide
DT	Digital Twin
DTEA	Digital Twin Element Architecture
EB	Energy Benchmarking
EC	Energy Consumption
ECI	Environmental Cost Indicator (NL: Milieukostenindicator, MKI)
EPB	Environmental Performance of Buildings (NL: MilieuPrestatie Gebouwen, MPG)
EPD	Environmental Product Declaration
EPI	Energy Performance Index
GFA	Gross Floor Area (NL: Bruto Vloeroppervlakte, BVO)
GHG	Greenhouse Gas
GIS	Geographic Information System
GWH	geWOONhout
IEA	International Energy Agency
IEQ	Indoor Environmental Quality
IFC	Industry Foundation Classes
KE	Knowledge Engine
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Analysis
LoD	Level of Detail
MP	Material Passport
NMD	National Environment Database (NL: Nationale Milieu Database)
NO_x	Nitrogen Oxides
NZEB	Net-Zero Energy Building

PM	Particulate Matter
SDG	Sustainable Development Goals
SoS	System of Systems
TBI	Group of Construction Companies
UNFCCC	United Nations Framework Convention on Climate Change

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1 Introduction

1.1 Background Information

The past years have seen a societal shift from environmentalism and sustainable development being seen as niche topics to them taking center stage in many political discussions. Finding solutions toward a more sustainable future is the defining problem of this generation. In 2015, the United Nations introduced the Sustainable Development Goals (SDGs), a framework of 17 interconnected, global goals aiming to achieve sustainable development by 2030 (UN, 2019). The SDGs most often connected to the construction industry are clean and affordable energy (SDG 7), responsible consumption and production (SDG 12), and climate action (SDG 13), with further connections to other goals depending on the project context (Gade et al., 2021; Johnsson et al., 2020; Secher et al., 2018). Especially focused on climate action, there is a large pressure from international and national sources to reduce greenhouse gas (GHG) emissions to limit the effects of climate change. In an international context, the most relevant environmental policies for the Netherlands are the UNFCCC Paris Agreement and the EU Green Deal. The Paris Agreement is a binding international treaty signed in 2015, focused on limiting global warming to 1.5°C (Paris Agreement, 2015). The EU Green Deal established in 2020 is an action plan for the EU to reduce GHG emissions by 55% until 2030 and reach climate neutrality by 2050 (European Commission, 2020). Both policies depend on national contributions, and the Netherlands adopted the Climate Act in 2019, committing to a GHG emissions reduction of 49% by 2030 and 95% by 2050. This is supported by the National Climate Agreement presented in 2019, which presents targets and strategies for reaching the national climate goal for different sectors, including the built environment (Ministerie van Economische Zaken en Klimaat, 2019).

Globally, the construction industry and buildings are estimated to be responsible for 34% of the final energy use, and 37% of energy- and process-related CO_2 emissions in 2021 (United Nations Environment Programme, 2022). Further, both building-related energy use and emissions are at an all-time high, which matches the trend of rising construction emissions in recent years (El Sheikh, 2022; United Nations Environment Programme, 2022). Despite the efforts to direct policy measures and investments at reducing both energy use and emissions, these efforts are unable to counteract the increasing emissions (United Nations Environment Programme, 2022). The Dutch government recognizes the impact this sector has on global emissions and wants to expend efforts to reduce emissions. It expects large potential for improvements in this sector, and consequently aims to reduce the construction sector's CO_2 emissions by 3.4 Mt by 2030 (Ministerie van Economische Zaken en Klimaat, 2019). Next to CO_2, nitrogen emissions are also a rising concern in the EU, causing nitrogen emission rules to be implemented EU-wide, also in the Netherlands (Meijer, 2019). Among the concerns about rising emissions, the Dutch construction industry faces another challenge, as the country is in the middle of a housing shortage that is expected to peak in 2025 (Gopal et al., 2020). Consequently, the construction industry needs to increase the number of homes renovated and newly constructed in the coming years (BTIC, 2021). However, construction projects are often hindered by environmental regulations (Boztas, 2023; Meijer, 2019). Hence, the construction industry will need to decrease its emissions and develop innovative strategies to counteract rising emissions.

The 'Construction Technology and Innovation Center' (NL: 'Bouw en Techniek Innovatiecentrum', BTIC) is a public-private partnership, founded to further innovation in construction using insights from the government, businesses, and knowledge institutions (BTIC, 2019). In efforts to work towards a sustainable construction industry, the BTIC launched the innovation program 'Emission-free Construction' (Emissieloos Bouwen) to reduce emissions of NO_x, CO_2, and PM from mobile equipment

(BTIC, 2021). The program's goal is to provide research and developments that can be implemented within the next few years to achieve a 60% reduction in NO_x emissions, a 75% reduction in PM emissions from mobile equipment, and a reduction of 0.4 Mt of CO_2. To achieve these emission reductions, they defined seven sub-projects that will contribute to their efforts. Sub-project 4 of the 'Emission-free Construction' program proposes the use of industrialized or prefabricated construction methods to reduce emissions over the whole lifecycle of the building. They aim to optimize the processes and create more standardization in the products, processes, and supply chains. To further these developments, they highlight the role of digitalization in achieving data-driven lifecycle optimization.

Previously, the term industrialized construction was introduced, which is a collective term for different innovative construction techniques. Common techniques connected to industrialized construction include prefabrication, pre-assembly, modular construction, offsite construction, and transport and logistics innovation, all of which can be implemented in projects to various extents (B. Qi et al., 2021; Wuni et al., 2021). B. Qi et al. (2021) define it as a 'set of construction methods that advances the process from design through construction by employing intelligent manufacturing and automation techniques' (p.2). Other papers also highlight automation and intelligent manufacturing in relation to industrialized processes (Attouri et al., 2022; Wuni et al., 2021), and expand it to the standardization of products and processes (Attouri et al., 2022; López-Guerrero et al., 2022). Generally, the expected benefits of implementing industrialized processes are reduced construction cost and time, lower environmental impacts, and improvements in quality, worker health, and safety (Attouri et al., 2022; B. Qi et al., 2021). The connection between industrialized construction and sustainability has been a major research topic, especially concerning environmental sustainability performance indicators (Jin et al., 2018; López-Guerrero et al., 2022). The implementation of industrialized construction processes compared to traditional building processes generally improves environmental performance indicators, such as carbon emissions, energy use, material use, waste, and water consumption (López-Guerrero et al., 2022). However, the benefits are strongly dependent on the project and its conditions.

One of the supporting factors for the development of industrialized construction is the implementation of new, digital technologies (Attouri et al., 2022), as they help improve the quality of industrialized building systems (Azman et al., 2019). The implementation of these technological advancements in the industry, thereby using them to digitize production processes and connect the physical and digital world, is called Industry 4.0 (Pereira & Romero, 2017). Especially cyber-physical systems and the Internet of Things are characteristic of this concept, but other focuses are supply chain integration, and creating networked, automated production processes by implementing digital technologies (Alaloul et al., 2018; Pereira & Romero, 2017; Sacks et al., 2020). When this concept is applied to the construction sector, it is referred to as construction 4.0. While other industries have integrated these technologies broadly, the construction industry has yet to fully commit to their implementation, trailing far behind other industries in that regard (Abioye et al., 2021; Alaloul et al., 2018). Digital technologies applicable to the construction industry include different forms of monitoring and data acquisition (sensors, drones, GIS, GPS, etc.); data analytics (big data, AI, blockchain, etc.); communication systems (IoT); user interfaces (simulation, virtual reality, mobile interfaces, etc.); additive and robotic manufacturing; and software platforms and control (BIM, digital marketplaces) (Alaloul et al., 2018; Çetin et al., 2021; Sacks et al., 2020). Digital technologies are generally envisioned as important tools for the development of the construction industry, yet there is still a need for developing processes, policies, and organizational structures to facilitate their future implementation (Nikmehr et al., 2021; Sacks et al., 2020).

Sustainable development in the construction industry and its connected goals are reliant on using data acquisition, analysis, and management to achieve them (Mêda et al., 2021). Beneficial impacts on sustainability through digitalization in the construction industry can be optimized (energy) performance, resource and waste reduction, improved decision-making, reduced emissions, and lower construction costs (Alaloul et al., 2020; Bilal et al., 2016; Manzoor et al., 2021). This digitalization of construction processes and building operations creates large amounts of data. Yet, the use of advanced analytics, such as big data and AI, to interpret the collected data is still rare in the construction industry. This leaves much of the data collected through buildings unused (Abioye et al., 2021; Bilal et al., 2016). Integrating data analysis with other digital technologies in the construction industry is expected to improve construction processes and solve challenges the industry is currently facing, such as excessive generation of construction waste, resource consumption, scheduling delay, and budget overdrafts (Azis et al., 2012). Mainly, it is expected to increase the efficiency and productivity of the construction industry (Çetin et al., 2021; Nikmehr et al., 2021). Especially in terms of sustainable development, using these technologies to optimize policies, processes, designs, and functions in line with goals for sustainable development is perceived to have a large potential (Bibri, 2019).

Currently, BIM is the main focus of digitalization in the construction industry, providing the opportunity to digitally design, manage, exchange, and visualize information about a building (Alaloul et al., 2018; Çetin et al., 2021; Nguyen & Adhikari, 2023). However, BIM is a static form of modeling, only able to represent the building based on a virtual assessment, and unable to verify or adapt the representation based on the real performance of the building (Alaloul et al., 2018; Pottachola et al., 2022). Achieving these data-based optimizations will require the integration of real-time data and the use of data analysis tools not incorporated in the classic BIM structure (Deng et al., 2021). Consequently, the digital twin paradigm has developed in the construction industry. Digital twins (DTs) are cyber-physical systems that use data analytics to process real-time data and use it to intervene in the physical system (Al-Sehrawy & Kumar, 2021; Boje et al., 2020; Deng et al., 2021; Pottachola et al., 2022; Sepasgozar, 2021; Zhang et al., 2022). As they are capable of processing and analyzing unprecedented amounts of data, they can offer predictions; increase the buildings' efficiency in operations, management, and material utilization; and assist in minimizing lifecycle impacts (Al-Sehrawy & Kumar, 2021; Bibri, 2019; Boje et al., 2020).

Further, DTs are also able to improve the processes involved in making sustainable choices for buildings and assessing a building's sustainability. Currently, the assessment of sustainability indicators is complicated, as a lack of relevant data and human error hinder the ease of use (L. Li et al., 2020). There are many variations in the production process of materials in different areas and local standards of the industry (Khasreen et al., 2009). Further, there is a lack of available, transparent data considering these. Consequently, this elevates the need for accessible and standardized data inventories that are comparable on an international level. Further, due to the long lifespan of buildings, many assumptions about the components in future lifecycle phases are made in these assessments, making them less reliable (Hart & Pomponi, 2020; Khasreen et al., 2009). The implementation of big data technologies and continuous monitoring can increase the reliability of the assessments (Yoffe et al., 2022), which will also help to improve the reliability of decision-making for sustainability (Zavadskas et al., 2018).

DTs combine different aspects of monitoring, data analysis, and predictions that can advance sustainable development goals (Sepasgozar, 2021). Additionally, integrating the ambitions for sustainable development into the foundational research for this new paradigm will help to maximize the resulting environmental benefits (Bibri, 2019). Based on these findings, this research explores how the concept of DTs can be used in the context of industrialized construction to further the integration of sustainability concepts into their processes.

1.2 Problem Analysis

As the previous section pointed out, the concept of DTs could advance sustainable development goals. This section investigates problems regarding the use of DT to improve sustainability in the construction industry from the perspective of scientific literature and practice. The investigation of the implementation of DT in practice is conducted in cooperation with geWOONhout (GWH), an industrialized construction company in the Netherlands, which is the problem owner for this study. In the following sections, first, the problem owner is introduced, and the problem statement is based on their practical perspective. Next, the research gap is explored by looking at the scientific perspective in previous research. Both perspectives are combined to define the research objective, from which the research question is derived.

1.2.1 Problem Owner

The object of this study is the HOUTbaarHuis concept, produced by geWOONhout in a factory in Wehl. It was motivated by the development of a circular and CO_2-neutral alternative to traditional building methods (project coordinator, personal communication, 20/09/2022). The concept is a product-based house design, which aims for a sustainable, efficient, and modular building process, and allows for fast construction to counteract the current housing crisis in the Netherlands (geWOONhout, n.d.). Each house is constructed from several standardized, prefabricated building modules which are connected and stacked to build 2- or 3-story buildings. Each of these modules is individually assembled in an industrialized process in their factory and then transported by truck to the construction site to be placed and connected. There are several standardized layouts for the houses, which allow for a product-based production line. However, different exterior and interior finishes and some customer-specific for changes allow for a range of different project designs. The modular structure of the house and the reversible connections allow the house to be de- and re-mountable, on the module and component level. Further, the use of LVL wood to create the structure of the modules makes them lighter than a comparable concrete or brick structure. Additionally, using wood as a base material allows for screwed connections, lowers the carbon footprint, and increases the circularity.

The company aims for the highest level of prefabrication possible while keeping the houses affordable and sustainable. Further, they are invested in improving their designs through the use of data. For this purpose, they started installing sensors for monitoring indoor air quality parameters in their houses. Further, they are interested in using DTs to help improve their designs to increase their sustainability and guide related design decisions. GWH especially focuses on the use of sustainable materials, increased waste reuse, and recycling, and the reduction of CO_2 emissions in their complete operations.

1.2.2 Research Problem

Sustainability-related policies influence the operations of companies in the Netherlands, and many set their own goals to comply with them and protect their own interests. TBI, a major construction company in the Netherlands also set its own goals aiming for sustainable and circular construction, the digitalization of processes, and data-driven products and services (TBI, 2022). They want to provide market leadership in the construction industry towards reducing their environmental footprints and supporting the energy transition and circular economy transition in their processes. Next to minimizing the CO_2 emissions and energy usage, a need for the reduction of nitrogen emissions is emphasized, as high NO_x emissions led to projects being delayed or canceled during the tendering process. Further, the transition to a circular economy has their focus on using sustainable materials and making their materials, components, and buildings increasingly reusable.

Koopmans, a subsidiary of TBI, has launched the geWOONhout factory, aiming at the energy- and carbon-neutral production of houses (TBI, 2022). For improving the HOUTbaarHuis concept, the company also aims to further digitalize its project. While BIM and prefabrication are already standard practices for geWOONhout, they aim for a more data-driven approach to improving their designs and processes towards increased sustainability and circularity. They are interested in using big data to improve especially the material selection and energy efficiency and hope to integrate this with sensors they already install in their buildings. This data is currently only monitored and has yet to be consistently used to analyze and optimize the building's performance. Different case studies within TBI have shown the successful application of *DTs* in their projects, yet their interpretation of the term does not suit the interpretation used in this study. Nevertheless, geWOONhout found implementing a DT concept into their standardized operations difficult. They want to know more about how DTs can be used to further improve their processes and decision-making and what they would need to implement it for their company.

Based on the issues experienced by GWH in their implementation of digital twins, the following problem statement was formulated:

> *GWH aims to further digitize their design and production processes and intend on using a data-based approach for design decision-making and to increase the sustainability of their operations. Thus, they are interested in implementing DTs directed at sustainability in the future, but are unsure how they fit in their processes, what to use them for and what is needed to implement them.*

1.2.3 Research Gap

Existing literature places the focus of DT research mainly on theoretical concepts, while the research for implementation is still very limited (R. Carvalho & da Silva, 2021; Ozturk, 2021). In this theoretical research regarding DTs, investigating their connection to sustainability is uncommon (Ozturk, 2021), which is surprising as sustainability-related applications are often mentioned in theoretical research papers (Al-Sehrawy & Kumar, 2021; Boje et al., 2020; Mêda et al., 2021; Sepasgozar, 2021). Specifically, there is no paper that focused on exploring the role of DTs for furthering environmental sustainability (R. Carvalho & da Silva, 2021). Thus, the implementation of DTs should be further explored in connection with sustainability, especially environmental sustainability. It is necessary to identify how DTs can be directed at creating more sustainable practices and what processes they can be applied to specifically.

The implementation of a DT concept is still rare, and especially at a company level research is needed to explore the challenges these companies experience and identify possible solutions (Sepasgozar, 2021). However, there are different challenges that DTs present that might factor into the difficulties that companies are experiencing. First, there is a lack of a common framework for the design of a DT and a lack of methods or processes to develop such a design based on such a framework (R. Carvalho & da Silva, 2021; Lu et al., 2020; Sepasgozar, 2021). Thus, there is little understanding of how to implement them due to a lack of experience and guidance (R. Carvalho & da Silva, 2021). This also leads to a lack of practical evidence for the theoretical benefits predicted (R. Carvalho & da Silva, 2021). Further, when analyzing the progress of digitalization and implementing more sustainability-oriented practices, the 'lack of understanding of the processes and workflows required' (Olawumi et al., 2018, p. 67) and the challenge of adapting organizational processes (Alaloul et al., 2020) were identified as significant challenges. Especially traditional companies often struggle with developing digital services for a viable business model (Azkan et al., 2022), because they require a high level of integration between the existing business structure and the desired services (Koldewey et al., 2020). In summary, there is a lack of a structured process for designing and implementing DTs and facilitating their integration in the existing process structure of companies.

Broo & Schooling (2021) found a major challenge for the implementation and integration of DTs to improve sustainability into practice is purpose misalignment. This connects to the involvement of stakeholders in the process. Stakeholder involvement is a major component of creating a DT for sustainability, as they should collaborate to define processes and procedures for sustainable decision-making (Broo & Schooling, 2021; Zavadskas et al., 2018). As this form of cooperation is uncommon in the industry, it is important to work towards it, when aiming for sustainability (Broo & Schooling, 2021). This is especially important as they have their own interests, often related to their economic benefits, which makes it difficult to align their interests with sustainable development (Broo & Schooling, 2021). Without an overarching purpose for working towards sustainability, however, the DT is unlikely to support sustainable decision-making. This problem is worsened by a lack of research on the priorities of stakeholders for the development of sustainable construction practices (Lima et al., 2021). Consequently, stakeholders need to be an integral part of a sustainable process, and their knowledge needs to be integrated into the product created. Further, it shows that there is a gap between research and practice regarding the interests of companies in sustainability-oriented processes. There needs to be an analysis of the priorities of construction companies, focusing on their needs and the value DTs can create for them. It is important to overcome these challenges to implement DTs in the construction industry, thus planning for the involvement of stakeholders from the start is an important part of an implementation strategy.

The scientific literature has pointed out three major research gaps related to digital twins and sustainability. First, that while DTs can improve environmental sustainability, the implementation of DTs specifically aiming for sustainability has yet to be explored. Secondly, the lack of a structured process for the design and implementation of DTs. And lastly, the need to focus on the priorities of stakeholders and integrate the DT into their processes, especially to direct it towards sustainability. Thus, it is important to ensure that the DTs developed provide value to construction companies by aligning with their priorities for development and focusing specifically on connecting the concepts to their processes. Based on these conclusions from scientific literature, the research gap considered in this research is:

> *There is a lack of research on taking a structured approach to designing and implementing DTs that integrate into the processes of industrialized construction companies, especially in connection to their priorities and needs regarding environmental sustainability.*

1.3 Research Objective and Question

This research aims to support a company in developing an approach to DT implementation for improving their environmental sustainability. The company considered in this study is geWOONhout, which specializes in industrialized construction. Consequently, this study will also focus on the use of DTs in industrialized construction. Further, it aims to create a structured process that will help them design a DT and plan its implementation in their company. As the intention is to be able to implement the DT and integrate it into future operations, this study considers the current and future processes of GWH and their specific goals. Lastly, this study aims to support the design and implementation of a DT. To limit the scope of the study, this will be conducted at a strategic level, where a design and possible steps to implement it will be recommended. In summary, the following objective will be pursued in this study:

This research aims to give insight as to what sustainability-oriented DT applications would suit the needs of a modular construction company and suggest strategies for effective implementation.

Based on this objective, the following research question will be explored:

What DT applications can support GWH in environmentally sustainable decision-making processes related to their sustainability goals, and how can strategic recommendations for the implementation of these applications be developed?

2 Literature Review

The research question incorporates complex terms can have various interpretations. Consequently, they require more narrow definitions that will structure and scope the following research process. This chapter will explore three concepts, sustainable decision-making, modular construction and DTs in the construction industry.

2.1 Sustainable Decision-Making

The term *sustainability* in connection with its modern meaning has been used since the 18th century, stemming from the realization that the amount of wood taken from a forest should not exceed the amount regrown in the same time period to maintain the forest (Klöpffer, 2003). The term *sustainable decision-making* signifies any decision-making that 'contributes to the transition to a sustainable society' (Hersh, 1999, p.1). For this transition, to stimulate sustainable development, there must be a sustainable decision-making strategy supported by sustainability assessment and sustainability indicators (Waas et al., 2014). There are three aspects to consider for sustainable decision-making and the connected sustainability assessments and sustainability indicators. These are interpretation (context-specific interpretation of sustainability), information-structuring (operationalization, assessment, and communication of sustainability parameters to inform a decision-making process) and influence (influence on the decision-making process and sustainable development) (Hugé et al., 2011; Waas et al., 2014).

First, the interpretation of sustainability considered in this study is elaborated. The ASCE defines sustainability in the context of civil engineering as 'a set of economic, environmental, and social conditions in which all of society has the capacity and opportunity to maintain and improve its quality of life indefinitely without degrading the quantity, quality, or the availability of economic, environmental, and social resources' (Policy Statement 418 - The Role of the Civil Engineer in Sustainable Development, 2021). Thus, it is the intersection of environmental, social, and economic factors, and the sustainable development of urban areas and infrastructure should create a positive synergy between them. (Zavadskas et al., 2018). While it is important that all three aspects of sustainability are addressed to create sustainable processes (Kamali & Hewage, 2017), a decision was made to focus on the environmental aspects to limit the scope of this study. Primarily, because it is an important area of improvement in the construction industry (Lima et al., 2021), and there is a need for further research in this direction regarding DTs (R. Carvalho & da Silva, 2021).

The aspect of information-structuring needs to operationalize the information, e.g. through indicators, define how these indicators are assessed, and how they will be communicated to inform decision-making (Hugé et al., 2011). Consequently, a sustainable decision-making process should be based on sustainability indicators and assessments, which aid the understandability and conformity of the decision-making (Waas et al., 2014). In this case, a sustainability indicator should be a value providing an 'operational representation of an attribute' that is given meaning to though a reference value (Waas et al., 2014). The sustainability assessment is a process that contributes to understanding sustainability, helps to identify and assess sustainability impacts and fosters sustainability objectives (Waas et al., 2014). Lastly, the resulting values should be systematically structured to provide input for the decision-making process, for example through assessment schemes (Hugé et al., 2011). Consequently, any sustainability-related decision should be based on a sound indicator and assessment process that has been shown to contribute to making decisions based on sustainability.

The aspect of influence needs to consider the relevance that the aspect of sustainability has on the decision being made (Hugé et al., 2011). In industrialized countries, the environmental aspect of sustainability has historically been the most relevant (Klöpffer, 2003). Currently, the research related to sustainability in the construction industry focuses on environmental aspects, or environmental aspects in combination with economic, and/or social aspects (Lima et al., 2021). In contrast to this, practitioners in the industry consider economic interests to be the most important in their considerations (Kamali & Hewage, 2017), showing a rift between business and research interests. This is supported through claiming of a research gap in identifying the priorities of stakeholders regarding the sustainability aspects considered for their projects (Lima et al., 2021). Similarly, Broo and Schooling (2021) established, aligning stakeholder interests and sustainability measures is of utmost importance to achieve the SDGs. Consequently, this research will focus on developing recommendations for a modular construction company based on their environmental sustainability goals in an effort to ensure the influence of the DT on the decision-making process. When considering sustainability, there are often multiple stakeholders with different interests involved (Zavadskas et al., 2018). For this research the stakeholders will be limited to internal stakeholders in GWH and TBI.

Currently, environmental sustainability in the construction industry often focuses on material choices and consumption, water management, sustainability and environmental impact assessment methodologies, GHG emissions, energy performance, and energy efficiency strategies (Kamali & Hewage, 2017; Lima et al., 2021; Zavadskas et al., 2018). Machine learning has the potential support decision-making in these fields, for example through predictive control, optimization algorithms, monitoring, and real-time control to reduce the impacts of a building (Fnais et al., 2022). Further, it could ease the process of assessing the sustainability performance of buildings, for example by increasing the data availability and reducing the gap between performance prediction and actual performance (Alaloul et al., 2018).

This section has reviewed the different aspects of sustainable decision making related to interpretation, information-structure, and influence. Based on the review of these three aspects, a sustainable decision-making process in this research concerns any decision that has an influence on the environmental sustainability goals of GWH and is supported by one or more sustainability indicators and sustainability assessments related to these goals.

2.2 Modular Construction

Modular construction is a form of industrialized construction, which focuses on standardizing building modules, their off-site production, and their transport to the construction site, where they are assembled into a full building. Musa et al. (2014) define modular construction as 'a construction method that produces a building consist [sic] of modular units or modules, mass produce [sic] off site in a manufacturing facility. It includes the logistic and assembly aspect of it, done in proper coordination with […] planning and integration' (p.217). This method of constructing a building offers many benefits for the sustainability of the construction process and addresses several challenges the construction industry is currently facing. Sustainability challenges are addressed where modular construction reduces waste, costs, and construction time (Kamali et al., 2018; Musa et al., 2014). Further, it improves the reusability of building components, thus minimizing raw material use and production energy (Musa et al., 2014). In order to achieve these benefits, communication with all contractors and suppliers is an important component (Abdelmageed & Zayed, 2020; Molavi & Barral, 2016). Specifically, the stakeholders should be communicated to transparently, and they should be involved from the onset of the project to also contribute their expertise to the design and planning phases. Despite these expected benefits, a negative perception of modular construction techniques hinders its widespread application. Other barriers to modular construction include the constraints experienced through logistical limitations, and the increased complexity of the design and planning process compared to traditional construction techniques (Kamali et al., 2018).

While modular construction is considered a more sustainable construction process (Wuni & Shen, 2020), there is a significant lack of empirical data available to analyze the performance of modular constructed buildings. To assess the sustainability of modular construction processes it is important to include all lifecycle phases and a holistic view of sustainability (Kamali et al., 2018). However, the operational and end-of-life phases of the building are often disregarded in the assessment of the environmental performance of modular construction processes, and the insufficient data available lacks accuracy (Jin et al., 2020). Consequently, the data driven nature of DTs might aid in the collection, analysis, and interpretation of data related to this field.

To conclude this section, the literature has shown that modular construction generally works towards improving the sustainability of buildings. However, there is a lack of adequate empirical data about the performance of modular buildings which might be improved through the use of DTs.

2.3 Digital Twins in the Construction Industry

The concept of a digital twin (DT) was first developed by NASA (North American Space Agency) in 1970 for spacecraft, however, the specific term 'digital twin' was only adopted in 2010 (Pottachola et al., 2022). Currently, DTs are mainly used in the manufacturing industry, as the construction industry has yet to fully embrace the DT concept (Boje et al., 2020). A few articles regarding the use of DTs in construction were published between 2011 and 2016, but the concept has garnered wider interest since 2017 (Boje et al., 2020; Fang et al., 2022). This is partially related to the increased development of IoT systems, as these systems facilitate the implementation of the sensors in buildings and increase their affordability (Boje et al., 2020; Deng et al., 2021). With the DT concept only recently being adapted for the construction industry, there is a lack of a coherent definition (Opoku et al., 2021; Ozturk, 2021), thus defining DTs for this study is necessary as a basis for further DT development.

In order to create a DT, the process of DT development is relevant. Fang et al. (2022) identifies three evolution stages for developing DTs as shown in Figure 1. First, they identify a concept stage, which focuses on overarching characteristics that a DT should incorporate. The framework is more specific and shows different components of a DT and their connection with one another, while the method looks at specific technologies and systems that these components could use to fulfill the function of a DT. Based on this process, the methods chosen for a DT depend on a framework and its underlying conceptual characteristics. Consequently, developing a DT and identifying the methods needed for its implementation, requires defining the underlying conceptual characteristics and framework.

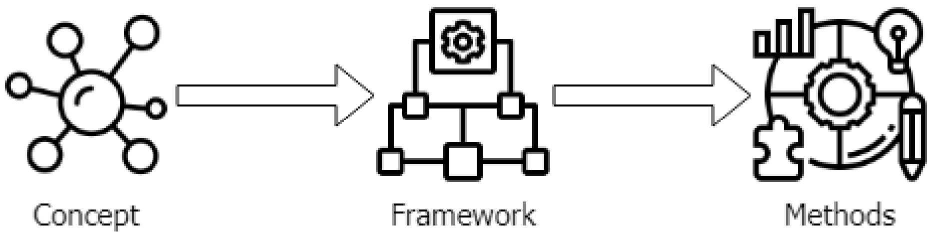

Figure 1: Evolution Process of DT Development (adapted from (Fang et al., 2022))[1]

[1] Icons through flaticon.com

This section explores the concept of DTs related to the construction industry and defines the concept of DTs for this study. Next, the benefits and challenges of this new concept are explored. Lastly, conceptual frameworks structuring DTs for industrialized construction processes are reviewed.

2.3.1 Conceptual Definition of Digital Twins in the Construction Industry

2.3.1.1 DT System Structure

DTs in the construction industry do not yet have an agreed-upon definition yet (Fjeld, 2020; Shahzad et al., 2022). Different researchers tend to formulate their own definitions, based on their viewpoint on the concept. While each piece of literature has its own specific definition and interpretation of what the specific characteristics are, there are general characteristics that are recurring in most articles. DTs are cyber-physical systems, with a physical system and a digital system representing it (Al-Sehrawy & Kumar, 2021; Boje et al., 2020; Deng et al., 2021; Grieves, 2015; Mêda et al., 2021; Pottachola et al., 2022; Sepasgozar, 2021; Zhang et al., 2022). Further, there needs to be a connection between these systems that allows them to communicate. Based on this general concept, Grieves (2015) first defined a general system of three components that make up a DT (Figure 2), consisting of (1) a physical entity, (2) a digital environment, and (3) a connecting data link. The physical component includes any physical entity, such as objects, structures, sensor technology, processes or people, connected to the physical system, while the digital component includes a collection of interlinked, semantically connected databases, engineering models and data analysis elements (Pottachola et al., 2022; Shahzad et al., 2022). However, the state of the physical environment may vary throughout a product's life cycle from a virtual description of a future product that contains the necessary data to build the physical product, to a real life instance if the product (Jones et al., 2020).

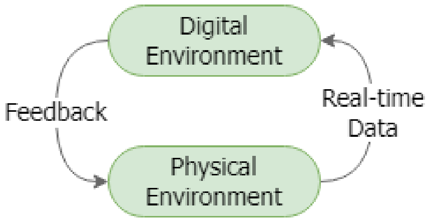

Figure 2: Basic Conceptual Model of a Digital Twin (based on (Grieves, 2015))

2.3.1.2 Data Collection and Communication

The collection of data plays a central role in the concept of a DT. The raw data is collected by the physical entity through the use of sensor technology or data bases and communicated to the digital system for processing and analysis (Ferré-Bigorra et al., 2022). Optimally, the data communication is continuous, thus enabling real-time data processing and synchronization between the digital system and the physical system. However, VanDerHorn & Mahadevan (2021) point out that requiring real-time data communication from the data collection technologies would also present a limitation to the usefulness of DTs, as some data might only be available at slower intervals, or the frequency of the data analysis might not require the collection of data at such frequent intervals.

In addition to the communication of data from the physical system to the digital, the digital system also communicates back to the physical system. This feedback loop is connected to a service that is based on the data received from the DT and may result in a change to the physical entity (VanDerHorn & Mahadevan, 2021; Zhang et al., 2022). Possible applications are monitoring, analysis, simulation and prediction, or optimization of the physical entity (Pottachola et al., 2022). Based on the type of feedback, DTs can also be classified into two categories, active DTs and passive DTs (Al-Sehrawy & Kumar, 2021). An active DT considers a system where the feedback is autonomously implemented in the physical system without any kind of human intervention, allowing the DT to actively affect the physical system. In a passive DT, the system gives feedback that needs to be interpreted and implemented by a human to affect the physical system. Thus, the two components are connected through bi-directional data communication, allowing both entities to affect each other.

Another important aspect of communication for DTs is interfaces. These interfaces are important points of connection between the DT and its users (Ferré-Bigorra et al., 2022). As such, they can have different purposes related to the control of the DT and the visualization of data. Typical interfaces found for DTs are dashboards, schematic diagrams, maps, 3D models, and virtual/augmented reality applications (Ferré-Bigorra et al., 2022). Especially the visualization of the data produced is seen as an important aspect of a DT to present the data in a manner that aids the decision-making process (VanDerHorn & Mahadevan, 2021). It means to guide the interpretation of the data, induce confidence in the decision made, increase the acceptance of the DT, or showcase the value of the DT (VanDerHorn & Mahadevan, 2021). This aspect is also expected to be of high importance for the cooperation with stakeholders (Tagliabue et al., 2021). Often, DTs have more than one interface, with each design being specific to the user (Ferré-Bigorra et al., 2022). The interface should generally be intuitive, adaptable, and easy to interpret, yet the depending on the user, the level of detail and information presented might change (Ferré-Bigorra et al., 2022; VanDerHorn & Mahadevan, 2021). Consequently, the consideration of interfaces and the visualization of data is central to the concept of a DT and its interaction with its environment.

2.3.1.3 Integration

Another aspect of DTs is that of integration. Three types of integration are frequently mentioned, integration of data sources, lifecycle integration and system integration. A large aspect of DTs is the integration of heterogenous data sources that might use different digital languages or vary in quality and temporal scope (Al-Sehrawy & Kumar, 2021; Zhang et al., 2022). First, data from all sources needs to be mapped, next duplicates need to be removed, and then the data needs to be fused and processed to enable a system to understand and analyze the data (Zhang et al., 2022). This process of integrating data sources is essential to the DT system. Lifecycle integration for the data analysis allows gaining insights for the future of the physical system and the design of new systems, leading to the achievement of long-term benefits (Al-Sehrawy & Kumar, 2021; Boje et al., 2020). To achieve full lifecycle integration, DTs are expected to integrate the different lifecycle stages of a building, such as design, construction, operation, and end-of-life. This means that the DT will develop with each stage of the lifecycle and adapt to changing purposes and challenges. This integration can further be expanded to integrate the DT over multiple lifecycles. Next, DTs should aim for integration on a system level, creating a so-called 'system of systems' (SoS) (Al-Sehrawy & Kumar, 2021). Buildings consist of different, interconnected systems, which should be integrated with the digital representation for the optimal use of a DT. This includes the internal systems of the building but can also extend to external interdependencies. In summary, integration on different levels is an important characteristic of DTs.

2.3.1.4 Definition of a Digital Twin

The previous sections provided a brief overview of the literature about the characteristics of a DT in the construction industry, which will be used to define the concept of a DT for this research. This overview revealed five major characteristics.

(1) Cyber-physical system with interconnected digital and physical components – There needs to be a digital environment (e.g. models, databases, and data analysis

components) and a physical environment (e.g. assets, sensors, processes, people), and they need to be connected through a data link.

(2) Integration – The system should provide an integration of data sources, lifecycle phases and systems.

(3) Bi-directional communication of data – There needs to be a data collection from the physical layer that feeds the digital layer, the data is used in the digital component, which creates feedback to the physical layer.

(4) Service – The system provides a service based on the collected data.

(5) Interface – There needs to be an interface that visualizes and communicates data and creates an (interactive) connection with the environment.

Consequently, this study defines a DT as:

> *A cyber-physical system that integrates data from different lifecycle phases and aims to provide a service to a modular construction company; that consists of a digital and a physical environment, and enables active or passive bi-directional communication between the environments; and that interacts with its users through an interface.*

Despite having identified these characteristics, it is often difficult to decide when the optimal DT is achieved (Fjeld, 2020). Thus, it is important to clearly outline what constitutes a DT and when it is considered appropriate for its purpose.

2.3.2 Benefits and Challenges of Digital Twins

When implementing DTs the expectation is to generate value for the project (Pottachola et al., 2022), but despite this expected increase in value DTs are still rarely implemented (Ozturk, 2021). This section explores the potential benefits and challenges connected to DTs that support this dichotomy.

DTs are expected to provide various benefits for their users. Specifically, DTs collect information throughout all lifecycle phases, which helps improve processes and support data-driven decision-making (Shahzad et al., 2022; Zhang et al., 2022). These ways of using information models help to increase the building's efficiency, minimizing a building's lifecycle impact and improving its lifecycle cost (Boje et al., 2020). They are also able to support environmental sustainability by reducing emissions and supporting clean energy developments, consequently helping to achieve the goals set by the SDGs (Boje et al., 2020; Sepasgozar, 2021). Additionally, they can aid the transition to a circular economy, for example, by collecting information about materials and components and assessing their potential for reuse and recycling, or by supporting the waste-free production of components (Mêda et al., 2021; Shahzad et al., 2022). Despite many potential benefits it is difficult to generalize them, as they strongly depend on the characteristics of the project and need to be evaluated separately for each project (Boje et al., 2020). Also, despite frequent mentions of a multitude of benefits, they are mostly theoretical in nature, as a DT providing them has yet to be implemented (Çetin et al., 2022). Thus, there is little proof that the advertised benefits are achievable, especially while still providing value to the business implementing it (Azkan et al., 2022; Çetin et al., 2022). Consequently, there is a need to implement DTs and verify their benefits. Another benefit of implementing DTs is that they can further the development of more elaborate DT technologies in the future. Firstly, the amount of data collected fosters machine learning capabilities for construction projects (Çetin et al., 2021).

There are different types of challenges that the implementation of a DT brings about. Among them are data management challenges, technical challenges, and stakeholder challenges. Data management challenges, such as privacy and data security, are a recurring topic in big data fields (Jain et al., 2016). Regarding the construction industry, the issues with data management include data privacy and security; data ownership, cooperation and sharing; and data liability and governance (Al-Sehrawy & Kumar, 2021; Shahzad et al., 2022; Zhang et al., 2022). These issues are difficult to solve and more research should be directed toward developing solutions to help the implementation of big data (Jain et al., 2016).

Next to the data management issues, the technical challenges surrounding the management of large amounts of data are significant. The major issue of heterogenous data sources and diverse data sources was discussed in the previous section. Yet, the issue remains, as the technical side of integrating these data sources and formats remains a challenge for creating DTs (Al-Sehrawy & Kumar, 2021; Broo & Schooling, 2021; Çetin et al., 2022; Deng et al., 2021; Shahzad et al., 2022). Next to the data itself, the standards and tools for the data are rarely interoperable, thus hindering progress in the integration of different data sources (Shahzad et al., 2022).

Lastly, the stakeholder-related challenges of implementing DTs in the construction industry hinder their development for use in buildings. Firstly, it is difficult to convince different stakeholders to share their data with other parties involved and work together for the implementation (Al-Sehrawy & Kumar, 2021; Broo & Schooling, 2021). Additionally, frequent changes to supply chains and stakeholders, and a lack of technical skills within the workforce contribute to this hesitation.

This section reviewed the benefits and challenges to the implementation of DTs. It found that there are many sustainability-related benefits, however, they depend on the application and structure of the DT. Further, the implementation of DTs is often hindered by lack of evidence for these benefits, which reiterates the importance of implementing DTs to verify them. Further, three categories for challenges to DT implementation were identified, data management challenges, technical challenges, and stakeholder challenges. These are important to rectify for the implementation of a DT.

2.3.3 DT Uses

The applications of a DT for construction are manyfold, reaching through the domains of monitoring, analyzing, predicting, and optimizing, which are applicable for various goals throughout all lifecycle phases of a building (Pottachola et al., 2022). A DT use is defined as one specific application in one process in the building's lifecycle (Pottachola et al., 2022). DT uses can help with: e.g. informed, impact-aware design; impact-aware construction; waste management; resilience of buildings; management of flexible spaces; management of building information; safety analysis; and emissions and energy management (Al-Sehrawy & Kumar, 2021; Boje et al., 2020; Çetin et al., 2021; Zhang et al., 2022). Nonetheless, Pottachola et al. (2022) propose to structure DT uses into five categories with increasing computational and composition complexity (Figure 3), (1) historical analysis, which uses historical data to improve the system in the present or the future; (2) simulation/imitation, which simulates the expected behavior of the system; (3) monitoring/ extraction, which collects data to emulate the real behavior of the system; (4) prediction, which aims to forecast the future behavior of the system; and (5) orchestration, which interprets data to take automated responsive action in the system through actuators.

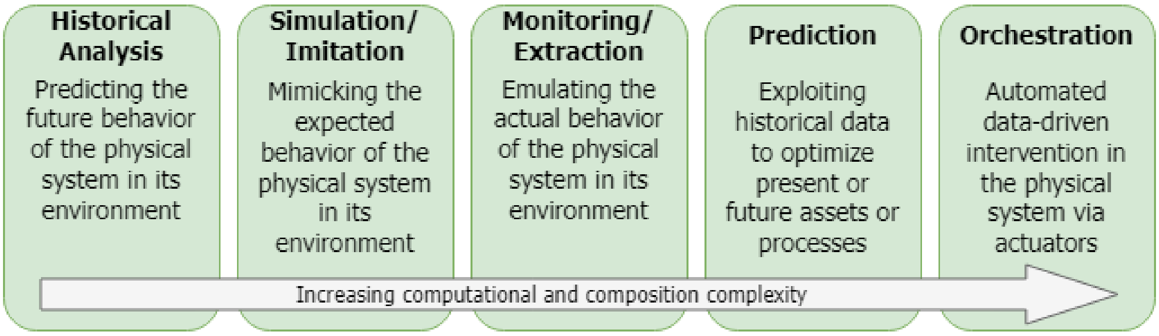

Figure 3: DT Uses Categories (adapted from Pottachola et al. (2022))

2.3.4 Digital Twin Frameworks

Identifying a framework for the architecture of a DT has been a major focus of research related to DTs (Çetin et al., 2022), yet different authors have outlined these frameworks in different ways and levels of detail. The most basic framework suggested contains three elements; a physical object, a digital system, and a bi-directional data flow as depicted in Figure 2 that were first suggested by (Grieves, 2015). In general, most frameworks include the three major components that Grieves identified but add more levels of detail. Thus, other scientific literature has adjusted this framework to expand and include other components. In a study on the concept of DTs and their applications, (Zhang et al., 2022) define a four-component framework, splitting the DT into (1) the physical environment, (2) the internet of things (IoT), (3) the digital environment, and (4) applications. These different elements are connected in a circular manner. Similarly, Q. Qi et al. (2021) developed a five-dimensional framework, identifying the physical entities, the virtual models, the services, and the digital twin data as major components that each link to all other components. The link between all of the components is a communication element that represents the fifth dimension. Da Silva Mendonça et al. (2022) reframes the DT in a hierarchical structure, identifying a layered architecture with the bottom layer relating to the physical elements of the DT and the top layer associated with the application of the results. This structure represents the general design of a DT application in the context of Industry 4.0. In summary, the elements of a DT and the structure of a framework for them is still contended as fiercely as its definition. All of the frameworks follow the exemplary structure of Grieves (2015), but then define different elements in differing complexity, each according to their own interpretation of what is relevant in their context. Consequently, a framework specific to this research and its context is needed.

2.4 Conclusion

This chapter reviewed three concepts of vital importance to this research, sustainable decision-making, modular construction, and the concept of a DT in the construction industry. Throughout these reviews, the following fundamental findings for this research were made.

- In this study a sustainable decision-making is any decision-making process that has an influence on the environmental sustainability goals of GWH and uses indicator(s) or assessment(s) related to these goals.
- DTs could aid in gaining, analyzing and interpreting empirical data for the modular construction industry, especially also data related to sustainability.
- To develop a DT, one needs to define a concept and a framework, which leads then to identifying the methods.
- The concept of a DT in this research is defined as an integrative cyber-physical system aiming to provide a service, consisting of a digital and a physical environment, that enables bi-

directional communication between the environments, and interacts with its users through an interface.

- There are different DT frameworks for different contexts and purposes, thus this research requires a context-specific framework to fulfill its purpose.
- The benefits of a DT can vary depending on its application and structure, and due to the lack of implemented DTs, the expected benefits are rarely validated.
- Data management, technology, and stakeholders are major challenges to the implementation of DTs.
- A DT use is a specific application of a DT in one life cycle phase, and currently, there are five categories of DT uses identified (see Figure 3).

3 Research Design

The previous section conducted a literature review to explore the concepts of sustainable decision-making, modular construction, and DTs in construction to provide a basis to define more specific research sub-questions. Based on these sub-questions, the methodology of the research will be structured and defined.

3.1 Research Sub-Questions

In Section 1.3, the research question to be answered in this study is defined as:

> *What DT applications can support GWH in environmentally sustainable decision-making processes related to their sustainability goals, and how can strategic recommendations for the implementation of these applications be developed?*

To answer this research question, the research is divided into more specific sub-questions. One finding discussed the importance of a DT framework to develop a DT, and that this framework had to be individual to the context. Thus, this research defines a framework fitting its context and develop a process to derive strategic recommendations from it. This framework is then validated through a case study, which implements the framework for DT uses supporting sustainable decision-making. These DT uses were chosen according to the problem owners priorities. The literature review also found that for sustainable decision-making there needs to be a definition of sustainability which the DT uses influence. The sustainability definition is aligned with the sustainability goals of GWH to comply with the research question. As it was found that DT uses are connected to activities in the company, only DT uses connected to activities that can have an influence on sustainability are considered. As a next step, the DT uses have to be chosen, and then the case study will be conducted to verify the framework and the process for deriving strategic recommendations. Consequently, it will follow these four sub-questions:

(1) What structural elements of a DT need to be considered to create a DT for modular construction, and how can recommendations for its implementation be derived from these elements?

(2) What sustainability goals does GWH have and what activities they conduct contain decisions that have an influence on these sustainability goals?

(3) What DT applications could support sustainable decision-making related to these processes and how can they be prioritized for the case study?

(4) What strategic recommendations for the implementation of a DT for specific DT uses can be given to GWH?

3.2 Methodology

This section will reflect on the methodology applied to answer the research question with its sub-questions, and achieve the goals set for this study.

3.2.1 Research Strategy

The choice of research strategy was based on the research aim, the available resources, and the ethical implications of the study (Johannesson & Perjons, 2021). The research gap identified the lack of a structured process that performs the functions this research wants to deliver, and little has been researched on the topic of the research question. Consequently, this research will be solution-oriented and use qualitative data, such as interviews, focus groups, and literature reviews, which allows the detailed study of a subject or process, using diverse data collection methods (Creswell, 2014). The data sources for these collection methods will include both primary sources, such as interviews and focus groups, and secondary sources, such as scientific and practice-oriented literature. The literature review assessed that a context-specific framework needs to be created to develop a DT. Thus, a theoretical framework that assists in planning the DT implementation was created based on scientific literature and then verified and validated through a case study. For the case study, a design science approach was chosen to create an artefact based on the theoretical framework. The process should show its application for specific DT uses and demonstrate its use in planning DT implementation.

The design science approach was chosen as it is directed at the design of an artefact, and will be able to achieve an in depth look at the process and content of the framework and its suitability for the intended purpose (Johannesson & Perjons, 2021). Another advantage of case studies is that they allow the study of a situation in a real-life context (Yin, 2009). This is important for this study, as the focus is on planning the implementation of a DT in a real-life context, the complexity of which would be difficult to mimic in an artificial setting.

The construction company GWH is the subject and problem owner of this case study. This specific case was chosen to combine three important aspects for conducting this research, (1) the company strives for a (more) sustainable production process, (2) the company uses modular construction techniques to assemble its houses, and (3) the company is interested in the implementation of DTs to improve their processes. To protect the privacy and competitiveness of GWH and any involved employees, all information is anonymized and published with their explicit consent.

3.2.1.1 Design Science Research Approach

For the case study, a design science research approach will be used. It will follow the process from (Johannesson & Perjons, 2021), which contains five steps to be taken to construct and verify an artefact through design science research, as shown in Figure 4.

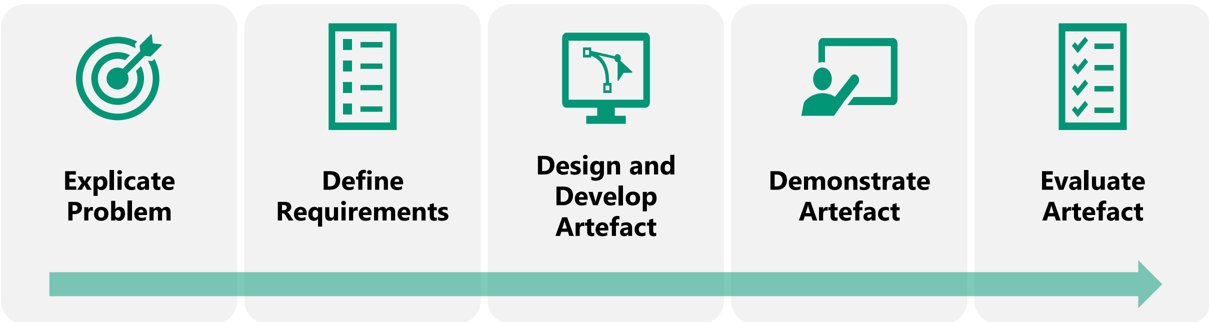

Figure 4: Design Science Research Approach (based on (Johannesson & Perjons, 2021))

Design science research starts with a practical problem to be investigated during the design science research. If a problem is not found, the research can also be driven by a curiosity rather than a problem. Nevertheless, the significance of the research to the practice and the general interest should be established. Using the problem definition, the requirements for the artefact need to be defined. This definition should address the outline of the artefact and how what it is supposed to look like. Then, the problem is translated into requirements that will be used to develop the artefact. These requirements will be based on the problem, previous research and solutions, and stakeholder interests. Then, the artefact has to be designed to solve the problem identified while fulfilling the requirements. Then, the artefact is verified by demonstrating its function. Lastly, the artefact is evaluated to determine whether the artefact fulfills the requirements and solves the problem. This research will use a requirements and development focused research, where there is a short problem explication, then an extensive requirement development that leads the artefact development, then demonstrate that the artefact is usable and perform a lightweight evaluation (Johannesson & Perjons, 2021).

3.2.2 Research Approach

The research was structured along the four sub-questions, which provided the input for answering the research question. The first three sub-questions were used as input for the case study, which answered the fourth sub-question. Figure 5 shows the connection between the research questions, and different in- and outputs.

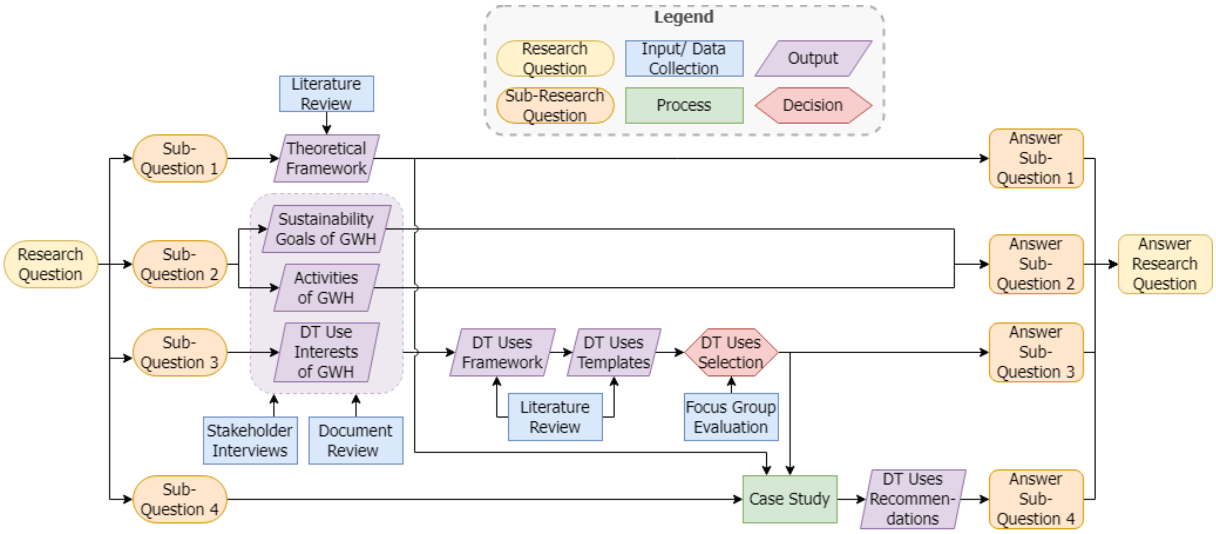

Figure 5: Research Approach Flowchart

The first sub-question developed a theoretical framework for DT implementation planning, which was the scientific input for the case study. The second and third research questions collected information about the goals, interests and processes of GWH, that provided the input for the problem analysis in the case study. The third research question also identified DT uses relevant to GWH and selected the DT uses considered for the case study. Then, the fourth research question was answered through conducting the case study, which used a design science approach to derive recommendations for the implementation of the selected DT uses. The process of answering each research question will be explained in more depth in the following sections.

3.2.2.1 Sub-question 1: Theoretical Framework

The first research question aimed to develop a theoretical framework, which was applied and validated through the case study in the fourth research question. The literature review concluded that this framework needs to be context-specific for its application. Thus, a literature review on frameworks regarding the construction sector, specifically the modular-construction sector was conducted. For this review papers were identified using the Scopus search engine for terms related to ‘DT framework’. Their abstracts were then scanned to identify papers of relevance, which were then regarded to identify possible frameworks. Of the frameworks found in literature, one was chosen as the foundation of the framework developed for this research. The framework was selected based to have the highest context-specificity, and a high level of detail (LoD).

The chosen framework was further developed through a thorough literature review of the needs for DT implementation. The literature for this review was identified through the Scopus search engine, using search requests related to 'DT implementation in construction', 'DT implementation in modular construction', and 'DT implementation in sustainable construction'. The results were then scanned by their abstracts for their relevance to the study. The relevant papers were then reviewed to identify any missing elements in the framework, and to collect more detailed information about the identified elements. Then, the information collected on each element was transferred into a framework, providing a visualized structure of the elements, and a set of questions to define each element for implementation planning.

Lastly, a process for deriving recommendations from the framework was created. For this process literature regarding the development of strategies and recommendations was identified through the Scopus search engine. The papers were filtered based on relevance for the topic through their abstracts, and then relevant papers were used to identify a suitable method for the process of developing the recommendations.

3.2.2.2 Sub-Question 2: Sustainability Goals and Related Processes

The second sub-question had two intended outcomes that help to orient the DT uses towards sustainable decision-making. First it identified the sustainability goals of GWH, and secondly, it identified the processes of GWH that include decision-making processes that will influence these sustainability goals. Therefore, data about the goals of GWH that are related to environmental sustainability, data about the different process activities in the company, and data about the decisions made in each process activity are needed.

To identify the necessary data, exploratory interviews were conducted with the director and the project coordinator of GWH, to gather information on the sustainability goals, the general processes of GWH, any documents related to the processes and sustainability goals. Further, other key stakeholders with relevant knowledge on the processes and the decisions made in them were identified. The final list of interviewees and their expert knowledge areas are shown in Table 1.

Table 1: Expert Interviewees

Role	Expert Knowledge
Director	Business Structure, Overview of Processes, Future Goals
Project Coordinator	Project Development, Engineering, Transport
ERP Integrator	Engineering, Production
Product Coordinator	Product Development

The sustainability goals were identified based on the information from the director and the project coordinator. They were asked about the environmental factors considered, the parameters assessed for these factors, and their goal for these factors. Documents about sustainability goals were asked for, but were not available at the time of the interviews. The processes and decisions made in them were identified based on a process flow report (NL: procesflowrapport), and the interviews with the project coordinator, the product coordinator and the ERP integrator. Based on the identified processes and the identified decisions, the processes relevant for this study were selected.

3.2.2.3 Sub-Question 3: Potential DT Uses and DT Uses Selection

The third sub-questions aimed to identify potential DT uses that are of interest to GWH, and then select two DT uses to conduct the case study with. This question is answered in three consecutive steps, first, the company interests are identified, then, the possible applications are selected according to their estimated suitability for the case study, and lastly, the estimated suitability is verified through an evaluation with GWH.

Step 1: DT Uses Interests

First, to identify the information needed for the second criterion, the interests of GWH regarding DTs are identified. To collect this information, interviews with the key stakeholders listed in Table 1 were conducted to identify these interests. In the process they were asked what current issues they see in their field that could be improved through technology-based solutions, and what their future goals they could imagine for their sector.

Step 2: Potential DT Uses and DT Uses Templates

This step identifies potential DT uses that are estimated to be suitable for the case study based on the three criteria defined before, sorts them based on their DT use categories, and the activity they belong to in the DT Uses Framework, and then defines their characteristics using the DT Uses Template.

This section utilizes two frameworks developed by Pottachola et al. (2022). First, the DT Uses Framework (see Appendix A: DT Uses Framework), which connects a DT application to a specific activity (rows) and a DT uses category (columns). This allows a fast overview of the DTs, and their expected computational and composition complexity (see Figure 3). Secondly, the DT Uses Template (see Appendix B: DT Uses Template), which provides a standardized structure to identify important characteristics of a DT use. This facilitates a common understanding and showcases its needs and benefits to other stakeholders. The DT Uses Template collects a description of the DT use and its processes, the expected benefits, the required data and technology resources, required competencies, and presents a generic IS structure.

To identify DT uses, scientific literature was reviewed. Through the Scopus search engine papers related to 'DT uses', 'DT applications', 'applications of cyber-physical systems', and 'sustainable DT uses' were identified, which were scanned for relevance based on their abstracts. Due to the multitude of possible applications of a DT in construction, three criteria were chosen as characteristics of a DT use that represent their suitability for the case study.

The first two are a *sustainability connection* and *value to the company*, which correspond to the aim of this study (see Section 1.3) to find DT uses that are related to sustainability and suit the needs of the company. To estimate the value of a DT use to the company, the interests of the GWH regarding DTs will be identified to match the DT uses to their needs. The third criterion is *feasibility*, as it is important that any DT use selected can be applied to the intended case study, which requires knowing how the DT is supposed to be implemented.

Consequently, the following selection criteria for potential DT uses will be applied:

(1) Sustainability Connection – The DT use needs support sustainable decision-making according to the definition in Section 2.1 and the sustainability goals identified in Section 5.1.

(2) Value to the Company – The DT needs to provide value to GWH as the problem owner to be considered eligible for this case study. To identify possible value, DT uses fitting their interests identified in Section 6.1 will be selected.

(3) Feasibility – To ensure that a DTEA can be created for a DT use, there needs to be enough information about the intended process available to fill in the DT Uses Template.

The research papers identified before were then reviewed to identify DT uses that fulfill the criteria and can be considered for the case study. These potential DT uses were then sorted into the DT Uses Framework, connecting them to a DT uses category and an activity of GWH.

Next, a literature review for each of the DT uses was conducted. The Scopus search engine was used to search for additional papers related to each potential DT use. Based on their abstracts their relevance for the review was determined. Then, the papers were reviewed regarding information relevant to the DT Uses Template, allowing the creation of the DT Uses Template for each potential DT use.

Step 3: DT Uses Selection

The third step selected the two of the potential DT uses for the case study. The estimated suitability of the DT uses needed to be validated by GWH to select the DT uses for the case study. A focus group of key stakeholders at GWH was formed to validate the three criteria. These stakeholders needed to have an oversight of all processes to evaluate how each DT use would fit their operations, and an understanding of the sustainability impacts it could have. Consequently, the director and the project coordinator were selected in cooperation with GWH for the focus group.

The validation process included presenting the DT Uses Template of a potential DT use to the focus group, then having the focus group members discuss the criteria for the DT use among them, and lastly giving their opinion on whether the DT use fulfilled the suitability criteria and to what degree it fulfilled them according to an evaluation scheme. This evaluation scheme is presented in Table 2. It uses the three DT uses selection criteria, and defines them from the perspective of GWH. Further, asks the participants to rate each DT according to the degree of which the criterion was fulfilled. This rating has four levels, from low (0) to high (3), which are explained in more detail for each criterion in Table 2. The evaluation process was repeated for all DT uses.

Table 2: Evaluation Scheme for the Suitability of Potential DT Uses

		Criteria		
Pts	**Rating**	**Sustainability Improvement**	**Value to Company**	**Feasibility**
3	High	DT is addressing an aspect where large sustainability improvements can be expected.	The DT adds critical value to the company, and significantly improves existing processes and services.	DT could be implemented into the company structure and processes immediately and with little effort, competencies and data needs will be met.
2	Moderate	DT is addressing an aspect where sustainability improvements can be expected.	The DT adds value to the company or improves existing processes and services.	DT could be implemented into the company structure and processes within the next few years by adapting them to new workflows, competencies will need to be improved and more data collected.
1	Acceptable	DT is addressing an aspect where the sustainability improvements might be achieved.	The DT could provide limited value to the company in the future or provide insignificant improvements to the processes and services.	DT could be implemented long-term, with significant changes to the company structure or processes, new competencies and data collection methods need to be acquired.

		Criteria		
Pts	**Rating**	**Sustainability Improvement**	**Value to Company**	**Feasibility**
0	Low	DT is addressing an aspect where the sustainability is not expected to improve.	The DT would not add value to the company and cannot be used to support processes or services.	DT is not implementable in the foreseeable future within the structure and processes of the company, the competencies and data needs cannot be met.

Based on the results of the evaluation, the highest scoring potential DT uses were selected for the case study. In case of a tie, the focus group members were asked to order the tied DT uses according to their priorities to facilitate a selection.

3.2.2.4 Sub-Question 4: Case Study

The fourth sub-question was answered through a case study, which aimed to give recommendations to GWH for planning the implementation of the selected DT uses. Next to that, the case study verified and validated the theoretical framework, as well as it gave some insights into potential revisions. The process of the case study is conducted as design science research following the design science process introduced in Section 3.2.1.1. The design science process for the case study is shown in Figure 6, including the inputs and the outputs of each step. The following sections will describe the different steps of the design science process.

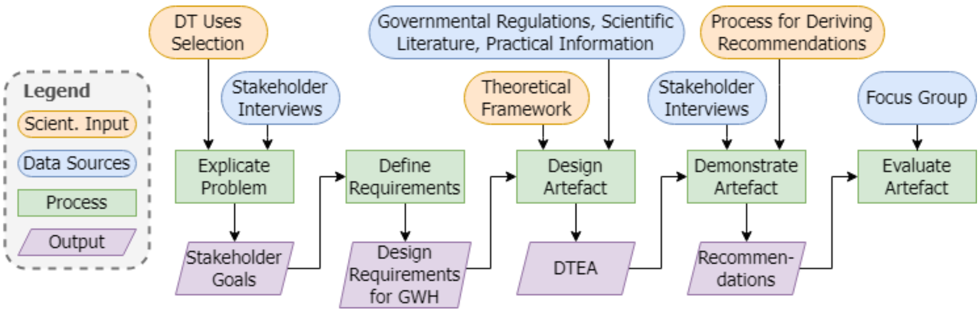

Figure 6: Design Science Approach for the Case Study

Step 1: Explicate Problems

The first step is the problem analysis, which was based on the DT uses selected in the previous sub-question. For the analysis data on the needs and goals of the company regarding the specific DT use was needed. This data was collected through stakeholder interviews with key stakeholders at GWH, that will potentially be involved in the future implementation of a DT. For the goals regarding energy benchmarking the project coordinator of GWH was interviewed, while for the BIM-based LCA a building physics expert from TBI was interviewed. The information gathered is used to formulate the goals of the stakeholders.

Step 2: Define Requirements

The requirements are based on the goals collected in the previous step. They define what needs to be considered in the planning of the DT design. The output are the design requirements of GWH for each DT use.

Step 3: Design Artefact

The artefact was designed based on the theoretical framework defined in sub-question 1, and in accordance with the requirements from the previous step. Additionally, information about the different elements and their contents was gathered through governmental regulations, scientific literature, and information taken from practical insights. This information was collected and structured to construct the DT Element Architecture (DTEA), which defines the intended DT elements and their structure.

Step 4: Demonstrate Artefact

The demonstration aims to verify that the framework can fulfill its purpose and show how it can derive recommendations from the DTEA created during the design step. This step used the process to derive strategic recommendations for DT implementation, using the gap analysis . It further needed information about the current situation of the company regarding the elements defined in the DTEA. This data was collected in stakeholder interviews with the experts from the problem explication. They were presented the DTEA to then assess what elements are available, might need to be adapted, or have to be newly established. Based on this assessment of the current situation in contrast to the intended situation shown in the DTEA, the recommendations were developed.

Step 5: Evaluate Artefact

The evaluation was carried out to validate the DTEAs and recommendations, but also the theoretical framework they were based on. It had three purposes, (1) to assess whether DTEAs designed meet their design requirements, (2) to assess whether the theoretical framework fulfills the purpose it was created for, and (3) to identify possible improvements to the theoretical framework. The first aspect is assessed through an informed argument, while the second and third aspects are assessed by a focus group involving key stakeholders of GWH.

This focus group consisted of four stakeholders that would be involved in the future implementation of any possible DT, which included the director of GWH, the project coordinator, a trainee focused on digital twin implementation, and a building physics expert from TBI. The focus group evaluation was conducted in two parts, first the evaluation of the results for each DT use, and then the evaluation of the framework in general.

In the first part, this focus group assessed whether the DTEAs and strategic recommendations created in the case study fit the research problem and gap defined in Sections 1.2.2 and 1.2.3. Five criteria were formulated for this assessment, (1) the degree to which the recommendations reflect their priorities, (2) the fitness of the recommendations to be integrated into the company processes, (3) the clarity of the overview of the identified elements in the DTEA, (4) the ability to plan the implementation based on the recommendations, and (5) the ability of the designed DT structure to help GWH achieve their sustainability goals. Each of these criteria is rated on a scale from high to low, with each degree explained in Table 3. The DTEA and recommendations of each DT use was presented to them, then they were asked to discuss the criteria and give a joint rating[2].

Table 3: Evaluation Criteria for the Case Study Results for GWH

Criterion	High	Moderate	Acceptable	Low
Reflection of priorities	The recommendations reflect our priorities exactly.	The recommendations are oriented towards our priorities, but do	The recommendations are oriented towards our priorities, but	The recommendations do not reflect our priorities.

[2] Due to time constraints, it was not possible to jointly discuss the criteria for the BIM-based LCA results, which led to each of the participant rating them individually, with one participant abstaining from the rating. The received ratings are presented separately and then averaged to the median vote.

Criterion	High	Moderate	Acceptable	Low
		not meet all our goals.	have major deficits.	
Integration into company structure/ process	The recommendations fit the company structure/ processes very well.	There recommendations are strongly connected to the company structure/ processes.	The recommendations are loosely connected to the company structure/ processes.	The recommendations cannot be connected to the company structure/ processes.
Overview of possible DT elements	The framework gives a clear overview of the elements needed for a DT.	The framework gives an overview of the elements needed for a DT.	The framework gives an unclear overview of the elements of a DT.	The framework does not resemble the elements of a DT.
Implementation planning	The recommendations enable directly outlining the necessary steps to create a DT.	The recommendations are helpful in outlining the necessary steps to create a DT.	The recommendations can support outlining the necessary steps to create a DT.	The recommendations do not help to outline the procedure of creating a DT.
Sustainability connection	The DT outlined by the framework is directly linked to us achieving our sustainability goals.	The DT outlined by the framework can help us achieve our sustainability goals.	The DT outlined by the framework can indirectly help us achieve our sustainability goals.	The DT outlined by the framework cannot help us achieve our sustainability goals.

The second part of the focus group evaluation intends to use an open-ended approach to get insights into possible improvements from a practical perspective. Thus, each participant was asked to give their opinion on four open questions regarding the principal idea of a DTEA and strategic recommendations.

The following questions were posed:

- What are the benefits of having this overview for the implementation of a DT?
- What do you see as major challenges for the implementation of the DT/recommendations?
- What value does it have to consider stakeholders in the DTEA?
- Are there any elements you felt the framework was lacking?

4 Theoretical Framework for DT Development Recommendations

This chapter aims to answer the first research question of this study:

> *What structural elements of a DT need to be considered to create a DT for modular construction, and how can recommendations for its implementation be derived from these elements?*

In the literature review, it was established that for the development of a DT a framework would be necessary, and that this framework would have to be specific to the context of this study. A theoretical framework was developed according to the procedure in Section 3.2.2.1. To fit the context of this study, the framework needs to be related to modular construction and aim for the implementation of DTs. More explicitly, the framework should help modular construction companies to design a DT and outline recommendations for them to implement the designed DT.

4.1 Conceptual DT System Architecture

In the literature review in Section 2.3.4, different DT frameworks were introduced, and a lack of a universal DT framework was identified. Further, a difference in the level of detail (LoD) of the frameworks was found to match the complexity of the intended result. For this study, a highly detailed and structured framework is searched, as the result should be able to give a detailed overview of the elements they will need for the DT implementation on a strategic level. The works of Da Silva Mendonça et al. (2022) and Q. Qi et al. (2021) provided such detailed frameworks. However, the conceptual DT system architecture for industrialized construction of Pottachola et al. (2022) provided a very detailed framework that was also directed at the modular construction industry and is intended as a tool to develop a DT in the construction industry. Thus, it was selected the most fitting framework for this research. The following paragraphs explain the original framework, and the adaptions made for this study. The final framework is shown in Figure 7.

Pottachola et al. (2022) created a conceptual framework for a general system architecture of DTs that describes the components necessary for a technical DT system in the AECO-FM industry. Similar to Da Silva Mendonça et al. (2022), it is a hierarchical and layered DT architecture. The framework divides a DT into interconnected layers, each with their own functionality. Each layer has a specific function it fulfills in the DTs structure. An overview of their conceptual DT architecture is shown in Figure 7 (green part). Pottachola et al. (2022) found that a DT has five tasks to accomplish at any given moment in time, (1) collecting data, (2) communicate the collected data, (3) store and process the data, (4) analyze the data to generate insights, and (5) intervene in the physical system based on those insights. Each of these tasks is carried out within the six layers of the DT system. The six DT layers are defined as (1) the data acquisition layer, which collects data from the real world, (2) the data transmission layer, which enables communication between the physical and digital environment, (3) the data storage & digital model/information layer, which stores the collected data and processes it to prepare for the data analysis, (4) the data analysis/knowledge engine layer, which analyzes the data to gain more in-depth insights that help the DT fulfil its purpose, and (5) the service layer, which interprets the results of the data analysis and uses it to intervene in the physical system, and finally (6) the physical layer, which all other layers are based on. Depending on the configuration of the DT, different elements can be included in each layer, however, all the layers need to work together and communicate to function properly.

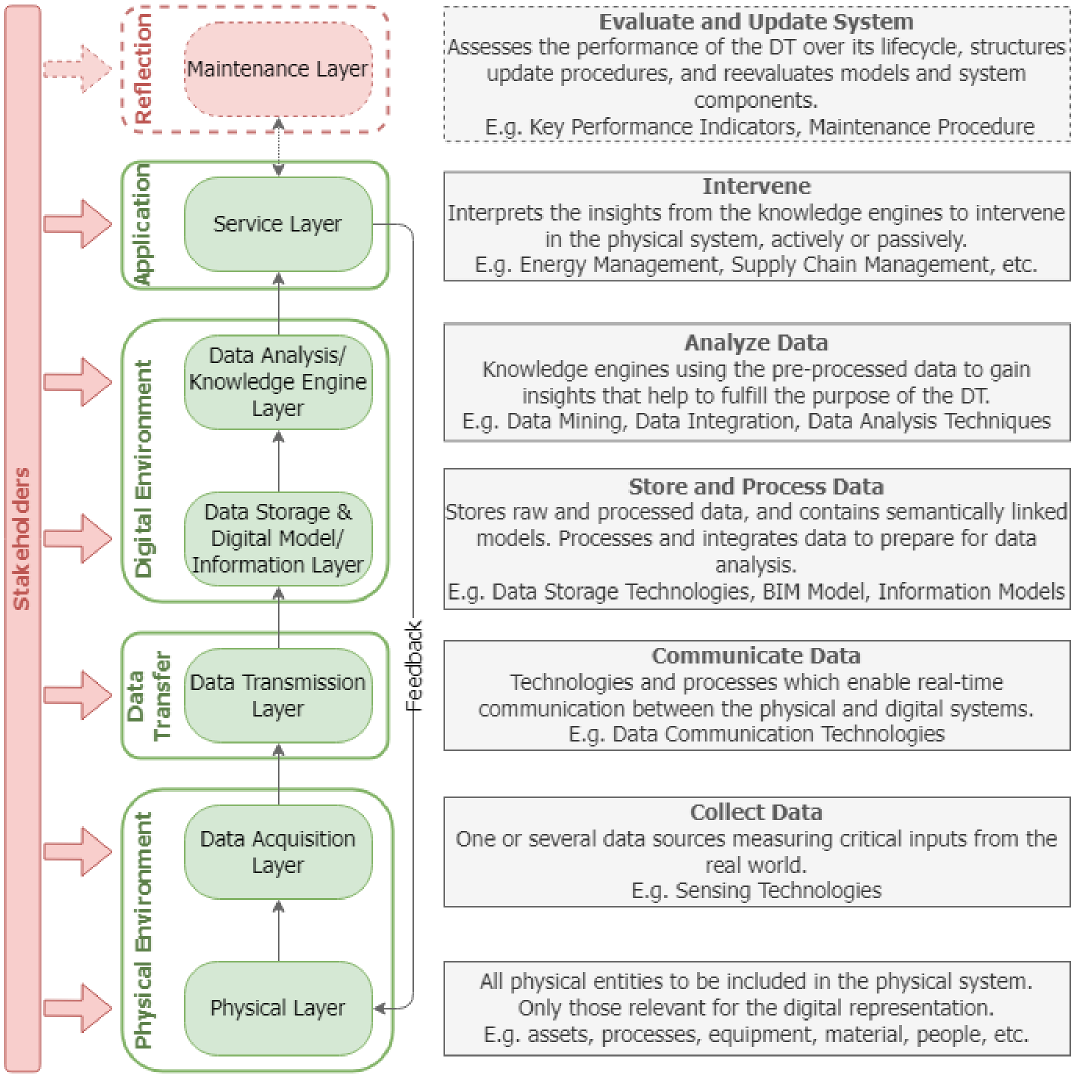

Figure 7: Conceptual DT System Architecture for Industrialized Construction by Pottachola et al. (2022) [green] Including Adaptions Specific to this Research [red]

Through a literature review on the elements important for the implementation of DTs, two missing parts for the DT implementation in a practical context were identified. First, the importance of stakeholders to the implementation of DT, and second, the importance of the maintenance of the DT throughout its lifecycle and the planning of this maintenance process before the DT implementation. Thus, these parts were added to the framework in Figure 7 (red part). The findings that led to the addition of these aspects are shown later in Sections 4.2.2.7 and 4.2.2.8.

4.2 Conceptual DT Element Architecture (DTEA)

The previous section reviewed scientific literature to define a DT framework that fit the context of this study. However, there is still a consideration to be made for the level of detail of the system architecture and how the process of planning its implementation should work. In the research gap, the lack of guidance on the development of a DT structure was highlighted. This section conducted a literature review to increase the detail by defining the contents of each layer, and build a framework that provides such a structured approach and guide the development of DTs for implementation.

First, this chapter argues that each DT layer should be split into several elements to make the resulting design more flexible. This is then integrated into the DT system architecture to form the more detailed

DT Element Architecture shown in Figure 9. Then, each of the layers and their elements are reviewed in literature to define their contents. Lastly, the identified contents are translated into questions for each element that need to be answered to design a structure that helps to plan for DT implementation.

4.2.1 Flexible System Architecture

An essential aspect of a DT is the flexibility of the system to adapt to new circumstances (Borth et al., 2019; Broo & Schooling, 2021; Lu et al., 2020; Tagliabue et al., 2021). This is critical when it concerns objects with a long lifespan, as the needs of the physical system it represents, but also the cyber-physical system itself might change over time (Borth et al., 2019; Lu et al., 2020). Additionally, the purpose of the DT and the stakeholders needs might evolve over time, which the DT should adapt to (Broo & Schooling, 2021). Only through adaptation can a DT remain an accurate twin, consequently it requires a flexible, scalable, and modular structure (Borth et al., 2019; Broo & Schooling, 2021; Moyne et al., 2020).

One way of ensuring the system's flexibility is separating the cyber-physical system into independent, logically linked models, instead of a single all-encompassing model (Shahzad et al., 2022). This can also allow different parts to be updated independently, and minimize the need to share data (Borth et al., 2019). Another suggestion is to ensure that the structure is not fixated on a specific technology (Broo & Schooling, 2021). Instead, the structure should focus on a specific goal and the required stakeholder involvement, and then build the data structure and its facilitating technologies based on this goal (Broo & Schooling, 2021). Similarly, VanDerHorn and Mahadevan (2021) imply a distinction between data processes and technology in their DT implementation research, and repeatedly refer to them as separate entities.

Based on these findings, this research suggests separating each layer of a DT into three elements; people, technology, and data; as presented in Figure 8, to enable independent planning and create a flexible DT system. Ideally, this enables the separation of data and technology to a degree where technology can be replaced without significant changes to the data structure. The data component in this case contains any elements related to the data flows, storage, and processes, while the technology includes any hard- or software needed to facilitate the intended processes in the layer. Further, a human component of DTs is integrated due to the addition of stakeholders to the framework. This addition is explained in more detail in Section 4.2.2.8. Other than the data and technology, which are inherent to the DT, the stakeholders were seen as part of the cyber-physical system, however, there are also stakeholders that act completely independent of the DT, but still have an influence on it (e.g. governments, data providers, etc.).

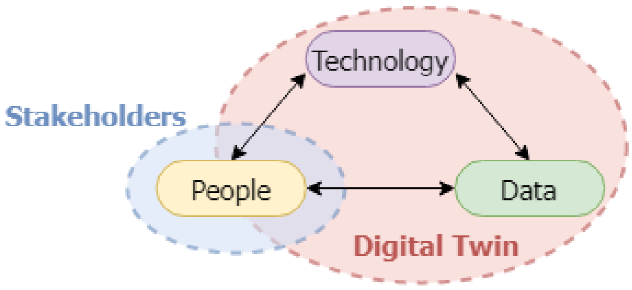

Figure 8: Separation of Components within Each DT Layer

Based on this separation, the DT Element Architecture (DTEA) was created. This conceptual version is visualized in Figure 9, and contains a three-part structure in which the stakeholders (yellow), data (green), and technology (purple) elements of each layer are shown. The next section discusses the elements identified in each layer, and their contents.

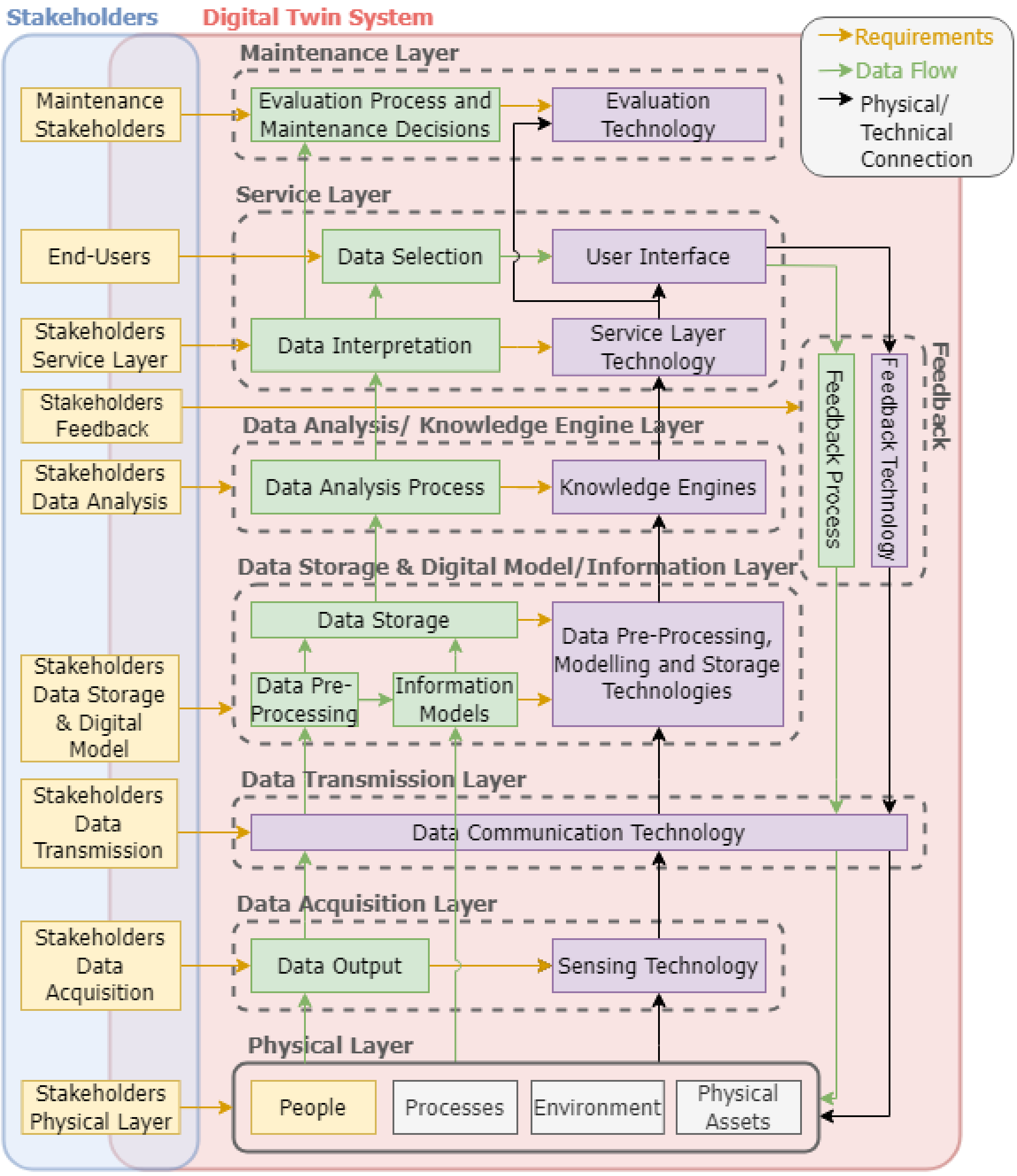

Figure 9: Conceptual DT Element Architecture (DTEA)

4.2.2 Defining the Elements of the DTEA

This section aims to give a clear overview of the contents of each element of the DTEA to create a plan of what is needed for the implementation process. Additionally, it helps to guide the development of a DT for a specific application. Hence, this overview is an integral part of the process to develop recommendations for DT implementation for a company. Based on the layers and their functions defined in Figure 7, a literature review was conducted to define the contents of each layer. Then, these contents will be condensed into guiding questions for each element of each layer, through which the specific elements for a DT use can be defined. These questions for each element of each layer will define a descriptive version of the DTEA. The further sections will review each layer starting with the physical layer, lastly the stakeholders are addressed more specifically in their own section. This stakeholder section will discuss the contents of the stakeholder elements in all layers.

4.2.2.1 Physical Layer

The physical layer encompasses the real-world system that is represented by the digital twin, including all physical entities and operations relevant to the service provided. This may include *(1)* physical assets, *(2)* processes, *(3)* people, and the *(4)* environment (Pottachola et al., 2022; Zhang et al., 2022). Based on these characteristics, the physical layer will concern the data of the physical layer, which encompasses the *people, physical assets, processes,* and *environment*, as well as the *stakeholders of the physical layer*. A technical element could not be identified for this layer.

VanDerHorn & Mahadevan (2021) highlight the importance of scoping the DT system considered. In defining the scope of the DT, one must consider what elements of the physical system should be considered in the virtual representation. This scope should be chosen to represent the physical system in the LoD required for the intended use, yet also be as simplified as possible to reduce the complexity of the model. Next to the components themselves, there is *(5)* a need for a hierarchical structure for the different components of the physical layer to simplify connecting different systems and their data streams to one another (Lu et al., 2020). Thus, the DTEA should include a hierarchical representation of the different physical elements relevant to the considered system.

Consequently, the following questions need to be answered for the physical layer[3]:

- Data
  - *(1)* What physical assets need to be considered in the DT system?
  - *(2)* What processes need to be considered in the DT system?
  - *(3)* What people need to be considered in the DT system?
  - *(4)* What environmental factors need to be considered in the DT system?
  - *(5)* What hierarchical structure can represent this data for the DT?

4.2.2.2 Data Acquisition Layer

The data acquisition layer collects data from the physical layer using sensing technologies installed in the physical environment. Consequently, the *data output,* the *sensing technologies*, and the *stakeholders of the data acquisition layer* were identified as elements. Based on these elements, the *data output* needs to define the data to be collected, while the *sensing technologies* need to identify what technologies are required to collect this data.

Data Output

The *(1)* data and *(2)* data quality needs should be defined, through assessing the needs of the DT application (Morewood, 2023). While there is no concrete definition of what represents data quality, its consideration can include data validation and structure, completeness, measurement certainty, representativeness, timeliness, spatiotemporal granularity uniqueness, data provenance, and data cleaning (Morewood, 2023). In order to assure the quality and quantity of the sensor data is satisfactory for the intended purpose, the necessary level of detail of the data needs to be defined (Pottachola et al., 2022). Further, the spatiotemporal granularity of the data collection system is important to the consideration, as it considers the collection frequency (time between measurements) and the sensor density (Ferré-Bigorra et al., 2022; Morewood, 2023). This affects the digital twin on multiple levels, as an increase in either will increase the fidelity of the data, yet also increase the computational capacity needed for the processing (Ferré-Bigorra et al., 2022). Consequently, a trade-off between quality and

[3] Further questions regarding the stakeholder elements in all layers are presented in Section 4.2.2.8.

cost must be considered. Further, the collection frequency might deviate from the transmission frequency, in which case data needs to be stored until transmission (VanDerHorn & Mahadevan, 2021).

Sensing Technologies

First, this element needs to *(3)* define how the necessary data is collected. Depending on the data requirements, a DT might employ one or more sources of data collection (Ferré-Bigorra et al., 2022; Lu et al., 2020). Sensors are the most frequently used data source for DTs, yet the types of sensors used vary depending on the DT use (Ferré-Bigorra et al., 2022). Next to the use of sensors, databases are a common source of data for DTs. Using a database based on separately collected data can also be relevant for design decisions and pre-construction use of data (Opoku et al., 2021). The *(4)* data quality should also be considered while choosing the data collection system for a specific application, examples are given in scientific studies considering the reliability; the granularity of the data, both spatial and temporal; the range and scalability of the sensors; and the measurement accuracy necessary to detect changes that are relevant for the system to work as intended (Jiang et al., 2022; Lu et al., 2020; Tagliabue et al., 2021). As another precaution for continued data quality, the sensors should fit their environment and not vary in reliability or functionality due to predictable outside factors, such as rain, wind, humidity, et cetera (Jiang et al., 2022). Another consideration for continued data quality should be given to *(5)* the lifetime of the sensors, as there could be changes to their reliability and accuracy (Borth et al., 2019).

Data Acquisition Stakeholders

Another aspect of data acquisition is *(6)* data ownership of the data collected for the DT (Bazaz et al., 2020; Pütz et al., 2022). Data ownership can be complicated, especially when several parties are included in the acquisition of the data (Bazaz et al., 2020). This makes it imperative to *(7)* find a regulation for the data ownership with anyone who might lay a claim to it, which helps to secure the permissions to collect, access, and use the data. Consequently, cooperation and potential agreements with stakeholders should be considered (Azkan et al., 2022; Nochta et al., 2019; Shahzad et al., 2022).

Based on this information, the following questions need to be answered for the elements[4]:

- Data
  - *(1)* What data needs to be collected?
  - *(2)* What quality should this data have (e.g. spatiotemporal quantity, accuracy, reliability, representativeness, etc.)?
- Technology
  - *(3)* What sensors and/or databases can be used to collect the data?
  - *(4)* What are the data quality requirements for these collection systems (e.g. reliability, granularity, range, scalability, suitability for environment)?
  - *(5)* What is the lifetime of these sensing technologies?
- Stakeholders
  - *(6)* Who owns the collected data?
  - *(7)* How can the use of the data be secured?

4.2.2.3 Data Transmission Layer

The data transmission layer represents the communication system between the physical and the digital environment using data communication techniques to provide (real-time) data transmission. In this layer

[4] Further questions regarding the stakeholder elements in all layers are presented in Section 4.2.2.8.

the *data communication technology* and the *stakeholders of the data transmission* were identified as elements. No data component was recognized.

The data collected in the data acquisition layer needs to be transmitted from the sensors in the physical system to a server or system in the data storage and digital model/information layer (Pregnolato et al., 2022). Thus, the transmission layer needs to provide a *(1)* transmission technology. It is also possible to consider more than one transmission technology, for example to transmit from multiple, heterogenous sources, or to synchronize discrete data sources before further transmission (Lu et al., 2020; Pregnolato et al., 2022). This can include multiple short- and long-range technologies (Lu et al., 2020). When deciding on a technology, *(2)* it is important to consider range and energy consumption of the technology, its suitability for the transfer of the data type, the communication frequency, and the reliability and security of the transmission (Lu et al., 2020; Pottachola et al., 2022; Pregnolato et al., 2022). While real-time transmission is often considered a prerequisite for DTs, VanDerHorn & Mahadevan (2021) criticize this assumption as restrictive since the communication frequency of the system might depend on the frequency of data availability and frequency of decision making based on the data. Lu et al. (2020) also state that the transmission frequency should be chosen to fit the DTs intended function. The technologies and transmission processes also needs to *(3)* adhere to regulations regarding the privacy and rights of all stakeholders concerned, and could potentially require setting up privacy agreements (Pregnolato et al., 2022).

Based on this information, the following questions need to be answered for the elements[5]:

- Technology
  - *(1)* What data transmission technology can be used?
  - *(2)* What are the requirements for the data transmission (range, energy consumption, data type, communication frequency, reliability, security)?
- Stakeholders
  - *(3)* What privacy rights need to be considered?

4.2.2.4 Data Storage & Digital Model/Information Layer

The data storage and digital model/information layer stores all data available for the DT, pre-processes it and integrates it into models to prepare it for the data analysis layer. Consequently, the data aspect consists of three sub-elements, the *data pre-processing,* the *information models*, and the *data storage.* Further, the layer includes the *data pre-processing, modelling and storage technologies,* and the *data storage and digital model stakeholders.*

Data Elements

There are two types of data supporting the operation of a DT, (1) dynamic data in the form of (raw) data collected from sensors or databases, and (2) static data in the form interconnected information models (Ferré-Bigorra et al., 2022; Pottachola et al., 2022). The use of the collected data to achieve a higher-level understanding is a key aspect of a DT (Zhang et al., 2022). However, DTs often collect immense amounts of (raw) data, and the data format is rarely suited to be analyzed directly (Pregnolato et al., 2022; Tao et al., 2019). Hence, *(1)* pre-processing the data is imperative to ensure the efficiency of the data analysis, this includes cleaning, converting and filtering the data (Tao et al., 2019).

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[5] Further questions regarding the stakeholder elements in all layers are presented in Section 4.2.2.8.

The *(2)* static data is comprised of digital models that contain information and visuals (Lu et al., 2020). The types of models employed, and their fidelity depends on the level of abstraction of the DT, but also on the LoD required for the DT application (Tagliabue et al., 2021; VanDerHorn & Mahadevan, 2021). Thus, the required models and *(3)* their LoD need to be explained in the DT structure. Despite being referred to as static data, also the data models might change over time, especially regarding the long lifespan of AECO-FM entities, thus these models should also be updated when necessary (Borth et al., 2019; Iskandar & Moyne, 2016; Tagliabue et al., 2021). Further, *(4)* the pre-processed dynamic data needs to be connected to the models of the physical world, which requires a set of definitive rules or a data integration schematic (Lu et al., 2020; Zhang et al., 2022). These connections between both types of data will also be defined in the DT structure. Next to the data flows, *(5)* the layer needs a system to store and manage the data produced by the DT (Lu et al., 2020).

Technology

It should consider the technology required to conduct the *(6)* data pre-processing, *(7)* modelling and *(8)* data storage (Lu et al., 2020; VanDerHorn & Mahadevan, 2021). Depending on the data collected, the DT might require large-scale storage systems which would also increase the costs of operating a DT (Lu et al., 2020; Pregnolato et al., 2022).

Based on this information, the following questions need to be answered for the elements[6]:

- Data
  - *(1)* How should the dynamic data be pre-processed?
  - *(2)* What models contain the static data?
  - *(3)* What LoD should these models have?
  - *(4)* How is dynamic data integrated into these models?
  - *(5)* What data storage is needed for the data?
- Technology
  - *(6)* What technology is required for the data pre-processing?
  - *(7)* What technology is required for the modelling?
  - *(8)* What technology is required for the data storage?

4.2.2.5 Data Analysis/Knowledge Engine Layer

The data analysis/knowledge engine layer is comprised of one or more knowledge engines (KEs) capable of using pre-processed data to discover patterns and other insights into the data (Lu et al., 2020; Pottachola et al., 2022). These insights will then be used by the service layer to achieve a higher understanding of the results and derive decisions and recommendations (Zhang et al., 2022). Consequently, the *data analysis process*, the *knowledge engines*, and the *data analysis stakeholders* were identified as elements.

Data Analysis

Thus, identifying what insights are needed for the service layer also defines *(1)* what insights the data analysis layer needs to produce and sets the aim for this layer. It uses the data stored in the data storage and digital model/information layer, and *(2)* conducts an analysis process through KEs (Lu et al., 2020; Zhang et al., 2022).

[6] Further questions regarding the stakeholder elements in all layers are presented in Section 4.2.2.8.

Technology

The *(3)* KEs used for this process need to be based on domain knowledge, and cannot easily be transferred, hence the KE(s) to provide the intended analysis process need to be domain specific (Lu et al., 2020). To facilitate the analysis and the connection to the data storage system, *(4)* different computational structures can be considered in the technology element. To select such a computing system, trade-offs between computation resources and transmission rates are important to consider. Three major approaches to the computational structure are cloud computing, edge computing, and fog computing (Ferré-Bigorra et al., 2022). The definitions of the different computational structures are given as:

- *Cloud computing* is "a way of using computers in which data and software are stored or managed on a network of servers (= computers that control or supply information to other computers), to which users have access over the internet". (Oxford University Press, n.d.)
- *Edge Computing* is "a distributed IT architecture which moves computing resources from clouds and data centers as close as possible to the originating source". (Simplilearn, 2023)
- *Fog computing* is "a decentralized computing infrastructure in which data, compute, storage and applications are located somewhere between the data source and the cloud". (Posey, 2021)

Cloud computing has a high computational capacity, yet limited transmission rates. It is also the most common structure, and has the advantage of low maintenance requirements. Edge computing has a limited computational capacity, but allows for high transmission rates, has a higher resiliency, and is easily scalable to larger networks. Fog computing provides a hybrid approach between cloud and edge computing and has mixed properties.

Based on this information, the following questions need to be answered for the elements[7]:

- Data
  - *(1)* What insights should the data analysis create?
  - *(2)* What data analysis process needs to be conducted to achieve them?
- Technology
  - *(3)* What KEs can support the data analysis process?
  - *(4)* What computational structure should the DT use to access the data storage?

4.2.2.6 Service Layer

The service layer of a DT interprets the output of the data analysis, processes the information in order to visualize it and control the feedback loop to the physical layer. Further, it provides an interface for the stakeholders by presenting the insights in the desired (visual) format (Lu et al., 2020; VanDerHorn & Mahadevan, 2021). Based on the complexity of this layer, it was decided to split it into three sub-layers the process of interpreting the insights, the user connection and the feedback. For the process the *data interpretation,* the *service layer technology,* and the *service layer stakeholders* were identified as elements. In the user connection, the *data selection,* the *user interface,* and the *end-user* were identified as elements. Lastly, in the feedback the *feedback process*, the *feedback technology*, and the *feedback stakeholders* were identified.

[7] Further questions regarding the stakeholder elements in all layers are presented in Section 4.2.2.8.

Process

The layer aims to interpret the insights created by the data analysis/knowledge engine layer at a higher level to support decision-making or give recommendations (Zhang et al., 2022). It needs to *(1)* define the supported decision-making process, *(2)* what insights are needed to support this process, and *(3)* what information or recommendations are its output (Lu et al., 2020). This interpretation process might need to be *(4)* supported through technologies that assist in interpreting the insights.

Based on this information, the following questions need to be answered for the process elements[8]:

- Data
  - *(1)* What decision-making process is supported?
  - *(2)* What insights are needed to support these processes?
  - *(3)* What information/recommendations are the output of the process?
- Technology
  - *(4)* What technologies can aid in interpreting the insights?

User Connection

To provide decision support to its users, the DT will need to create visualizations of the information for the end-users and stakeholders (Azkan et al., 2022; Lu et al., 2020; Pottachola et al., 2022; Tagliabue et al., 2021). The information presented should *(5&8)* cater to the information needs of the users. Especially information visualization is important for a DT, as it improves the communication with stakeholders, heightens the confidence in the model(s), and increase the DTs acceptance (Tagliabue et al., 2021; VanDerHorn & Mahadevan, 2021). Thus, a user-interface should always be considered for a DT. Recommended are *(6)* different interfaces for each stakeholder, as they should cater to a user's specific needs, interests and skills in the information it presents to them (Ferré-Bigorra et al., 2022; Lu et al., 2020; Pütz et al., 2022). Possible interface designs are e.g. dashboards, diagrams, maps, 3D models, virtual reality or augmented reality. Pütz et al. (2022) suggests four major criteria to *(7)* design an interface for digital services, focusing on (1) target group specific interfaces; (2) transparency, to allow users to trace the decision-making process back to the data acquired; (3) uncertainty, to communicate the uncertainty of the proposed feedback; and (4) ethical implications, considering moral dilemmas encountered in the process.

Based on this information, the following questions need to be answered for the user communication elements[9]:

- Data
  - *(5)* What information is of interest to the user(s)?
- Technology
  - *(6)* What type of interface should be created for the user?
  - *(7)* How should the information be visualized?
- Stakeholders
  - *(8)* Who are the user(s) of the DT?

[8] Further questions regarding the stakeholder elements in all layers are presented in Section 4.2.2.8.

[9] Further questions regarding the stakeholder elements in all layers are presented in Section 4.2.2.8.

Feedback

The service layer needs to *(9)* communicate the feedback to the physical system, thus the data transmission for the feedback is an important aspect of creating a DT (VanDerHorn & Mahadevan, 2021). For the *(10)* implementation of feedback, the DT can utilize actuators or similar equipment that allow the DT to change the condition of the physical system directly; otherwise, it can provide interfaces and visualizations that require human interpretation and action to implement changes to the physical system (Ferré-Bigorra et al., 2022). This allows digital twins to be *(11)* classified as active or passive (see Section 2.3.1.2) (Al-Sehrawy & Kumar, 2021). The *(12)* use of actuators can be either direct, by allowing the actuator direct control of a system, or indirect, by requesting a certain task or action to be carried out (Ferré-Bigorra et al., 2022). The type of actuator used varies depending on its intended application and the system it is applied to, yet indirect actuators are generally preferred as they have lower implementation cost.

Based on this information, the following questions need to be answered for the feedback elements[10]:

- Data
  - *(9)* What feedback is communicated back to the physical layer?
  - *(10)* How will the feedback be implemented?
  - *(11)* Is the DT active or passive?
- Technology
  - *(12)* What technologies might support the implementation of the feedback?

4.2.2.7 Maintenance Layer

Most DT frameworks reviewed consider all elements that the cyber-physical system needs to execute its intended function and provide the intended application. However, when considering implementing a DT, an insurance of its continued functionality over time is needed. Thus, there is a need for a maintenance process within the DT (Abdoune et al., 2023; Moyne et al., 2020). This is especially important for the models, as they might be 'affected by performance degradation over time due to intrinsic or extrinsic conditions' (Abdoune et al., 2023, p. 5). Thus, a maintenance layer was added to the framework.

Role of Maintenance

Different researchers view the role of maintenance in the DT differently. On the one hand, it is seen as part of the operational processes and the service aspect of the DT (Moyne et al., 2020), while others see it as a separate process that has its own place in the DT lifecycle (Abdoune et al., 2023). Often, it was presented as a reflection process on the DT's continued performance to decide whether it remains suitable for the intended purpose (Abdoune et al., 2023; Lu et al., 2020; Mêda et al., 2021; Moyne et al., 2020). It helps to maintain the DTs effectiveness and synchronization with the real-world system, but can also aid the communication of a DT's capabilities and the accuracy of its predictions (Abdoune et al., 2023; Moyne et al., 2020). Especially for active DTs with little to no human intervention, it provides a safeguard for the performance delivered (Borth et al., 2019; Lu et al., 2020; Mêda et al., 2021).

Maintenance Process

The scientific literature also suggests reflecting on different performance aspects of a DT. Generally, the use of key performance indicators (KPIs) is recommended (Broo & Schooling, 2021; Jiang et al., 2022; Moyne et al., 2020). Borth et al. (2019) suggest a two-part reflection procedure assessing system health,

[10] Further questions regarding the stakeholder elements in all layers are presented in Section 4.2.2.8.

which reflects on whether the system performs its intended functions in terms of the availability, correctness, and timeliness of data and processes. In another approach, Moyne et al. (2020) suggests to assess whether the DT is capable of delivering the intended service, reflecting on the achievement, validity and quality of the desired results. Other mentions of maintenance suggest that each model in the DT needs to be maintained to ensure its accuracy (Iskandar & Moyne, 2016; Uhlenkamp et al., 2022). Moyne et al. (2020) also suggests evaluating the severity of a DT not meeting the desired performance requirements, and assessing if the DT can continue operations and be updated, or it needs to be shut off immediately. Regardless of its structure, the maintenance should be robust and automated to allow for a continuous assessment (Borth et al., 2019; Iskandar & Moyne, 2016; Moyne et al., 2020). As a result of an assessment, the DT should conduct a (semi-) automated update processes (Borth et al., 2019). This process ranges from adaptions to the current system to recreating a new system (Moyne et al., 2020).

While studies that considered maintenance found it important, its consideration in DT-related studies was rare. Maintenance was mainly mentioned when considering the lifecycle of a DT (Abdoune et al., 2023) or defining requirements for DT design (Borth et al., 2019; Moyne et al., 2020), but it was considered an understudied area of DTs (Moyne et al., 2020). Maintenance processes were mainly based on metric performance assessment indicators, and the accuracy and synchronization of models. Both Borth et al. (2019) and Moyne et al. (2020) suggest highly varying elements in their reflection approaches. While Borth et al., (2019) focuses on the quality of data and the technical capacity of the system, Moyne et al. (2020) mentions the results and their quality as the main aspect. Remarkably, besides the general notions on performance assessment, little overlap on the purpose, processes, and execution of DT maintenance was observed. Further, other possible aspects relevant for maintaining digital systems were found to be completely lacking in literature. Potentially relevant are regular maintenance procedures, maintenance of the physical systems, updates to security and privacy processes, adaption of an expanding system, and other yet unidentified topics related to the continuous use of a DT.

The review of literature on the topic of maintenance of DTs revealed three important aspects:

I. Maintenance is an important aspect in the lifecycle of a DT system;
II. Maintenance considerations focus on performance assessment through performance indicators;
III. Many potential topics that could influence the maintenance of DTs that are understudied.

Especially for the long lifespan of AECO-FM assets, the extension of research on the maintenance of DTs should be considered for the implementation of DTs in the industry. However, there is little information on what this layer should include. Thus, this research concludes that further research is required before it can be properly integrated into a framework for DT development. While such a layer should be addressed in the future, this research will not include these considerations in the case study.

4.2.2.8 Stakeholders

The stakeholders have a special position in the framework, as they are not inherent to the DT itself, but separate entities connected to the DT. The conceptual DT system architecture does not consider these human factors, despite their potential impact the operations and preparation of the DT. It was found that stakeholders are crucial to interpret the results, for contributing their competencies, and for providing access to data resources. This importance for the involvement of stakeholders was addressed by (Broo & Schooling, 2021) by implementing them as their own component in their system architecture for cyber-physical systems. However, the paper does not address what influence they have on different aspects of the DT, nor how they affect the system. On the other hand, Ferré-Bigorra et al. (2022) have created a DT structure for an urban DT that includes stakeholders as a separate component while considering their connection to different layers of the DT. Thus, a stakeholder component was added to each layer to *(1)* identify them and their needs for different layers of the framework.

Contributing Competencies and Interpretation

First, *(2)* stakeholders make decisions and interpret the outcomes of the DT, which is an aspect often disregarded in literature (Zhang et al., 2022). Insights from DTs might be relayed to human actors, and they are responsible for making the decisions which will affect the physical system (Jiang et al., 2022). Further, they might *(3)* provide critical competencies which that are unavailable within a company and acquired through external sources, for example through cross-company cooperation (Azkan et al., 2022). Also, the system is utilized by stakeholders, its users, thus it should be designed for user-friendliness and cater to the user needs (Azkan et al., 2022; Çetin et al., 2022; Pütz et al., 2022). Additionally, the benefits of a DT can depend on the benefits provided to different stakeholders (Nochta et al., 2019).

Access to Data Resources

Stakeholder involvement is essential to address challenges for the implementation of digital solutions (Pütz et al., 2022). For example, DTs require a certain level of data availability and quality in their creation, yet decentralized data ownership and increasingly private data owners make sharing data complicated (Azkan et al., 2022; Nochta et al., 2019). Many stakeholders to refuse to share their data, due to a lack of frameworks to facilitate data sharing or privacy-related issues (Jain et al., 2016; Nochta et al., 2019). To remedy these issues, it is suggested to *(3)* cooperate with stakeholders and create reciprocity to influence their opinion (Jewapatarakul & Ueasangkomsate, 2022; Nochta et al., 2019). Especially important is an understanding of how their data is handled in terms of data security and ownership, also through contractual agreements (Azkan et al., 2022; Shahzad et al., 2022).

Based on this information, the following questions were identified for each stakeholder element in the framework[11]:

(1) What stakeholders are relevant to this layer?
(2) What decisions do they make?
(3) What competencies and data do they contribute?
(4) What data do they contribute?

4.2.3 Descriptive Conceptual DTEA

The previous section reviewed the different layers of a DT, and formulated questions for its elements. These questions are summarized in Table 4. The elements correspond to those shown in Figure 9.

Table 4: Descriptive DT Element Architecture

Layer	Stakeholders	Data	Technology
Maintenance Layer	What stakeholders are relevant to this layer? What decisions do they make? What competencies do they contribute? What data do they contribute?		

[11] The questions are not applied to the users of the service layer, as the whole sub-layer is directed towards stakeholder consideration.

Layer		Stakeholders	Data	Technology
Service Layer	Users	Who are the user(s) of the DT?	What information is of interest to the user(s)?	What type of interface should be created for the user? How should the information be visualized?
	Process	What stakeholders are relevant to this layer? What decisions do they make? What competencies do they contribute? What data do they contribute?	What decision-making process is supported? What insights are needed to support these processes? What information/ recommendations are the output of the process?	What technologies can aid in interpreting the insights?
	Feedback	What stakeholders are relevant to this layer? What decisions do they make? What competencies do they contribute? What data do they contribute?	What feedback is communicated back to the physical layer? How will the feedback be implemented? Is the DT active or passive?	What technologies might support the implementation of the feedback?
Data Analysis/ Knowledge Engine Layer		What stakeholders are relevant to this layer? What decisions do they make? What competencies do they contribute? What data do they contribute?	What insights should the data analysis create? What data analysis process needs to be conducted to achieve them?	What KEs can support the data analysis process? What computational structure should the DT use to access the data storage?
Data Storage & Digital Model/ Information Layer		What stakeholders are relevant to this layer? What decisions do they make? What competencies do they contribute? What data do they contribute?	How should the dynamic data be pre-processed? What models contain the static data? What LoD should these models have? How is dynamic data integrated into these models? What data storage is needed for the data?	What technology is required for the data pre-processing? What technology is required for the modelling? What technology is required for the data storage?
Data Transmission Layer		What stakeholders are relevant to this layer? What decisions do they make? What competencies do they contribute? What data do they contribute? What privacy rights need to be considered?		What data transmission technology can be used? What are the requirements for the data transmission (range, energy consumption, data type, communication frequency, reliability, security)?
Data Acquisition Layer		What stakeholders are relevant to this layer? What decisions do they make? What competencies do they contribute? What data do they contribute? Who owns the collected data? How can the data be secured?	What data needs to be collected? What quality should this data have (e.g. spatiotemporal quantity, accuracy, reliability, representativeness, etc.)?	What sensors and/or databases can be used to collect the data? What are the data quality requirements for these collection systems (e.g. reliability, granularity, range, scalability, suitability for environment)? What is the lifetime of these sensing technologies?

Layer	Stakeholders	Data	Technology
Physical Layer	What stakeholders are relevant to this layer? What decisions do they make? What competencies do they contribute? What data do they contribute?	What physical assets need to be considered in the DT system? What processes need to be considered in the DT system? What people need to be considered in the DT system? What environmental factors need to be considered in the DT system? What hierarchical structure can represent this data for the DT?	

4.3 Development of Strategic Recommendations Using the DTEA

While the DTEA structured the elements of a DT and intends to guide the planning of these elements, they should also be used to help companies plan the next steps towards DT implementation. Consequently, it is intended to use the DTEA to give strategic recommendations to the companies.

4.3.1 Goal-Specific Approach

Formulating recommendations for the company should be based on the design of the DTEA. To plan a DT, Pottachola et al. (2022) envision a top-down approach, which should 'start with a general idea of what you want and then add the details later' (Longman, n.d.). In relation to a DT, this implies that the expected outcome of the DT and the goal of developing it should be defined first, and the other elements will be designed to fulfill this goal. This approach is supported in other scientific literature. Broo and Schooling (2021) claim that a DT should be seen as 'an approach to operationalize data for supporting the implementation and assessment of the goals' (p. 22878) that are previously defined. Similarly, Lu et al. (2020) and VanDerHorn and Mahadevan (2021) claim that knowing the objective is the first step to a successful implementation. Thus, the design of the DTEA will be guided by a predetermined goal of what the DT should achieve. This goal should align with the goals of the company to focus on their priorities. In this case the goal is a specific DT use, that is intended for one specific activity in one specific process of the company.

4.3.2 Deriving Strategic Recommendations

A strategy is defined as a 'careful plan or method for achieving a particular goal usually over a long period of time' (Encyclopædia Britannica, n.d.). In this case the goal is to implement a DT for a company. Thus, the strategic recommendations recommend steps that need to be taken to implement the designed DTEA in the future. The planning of a strategy requires an assessment of the current situation and the intended developments (Grünig et al., 2022). Only when the difference between the current and intended state is clear, it can be derived what still needs to be achieved, which are the strategic recommendations. To clarify this difference, a gap analysis will be used as shown in Figure 10. A gap analysis is a 'tool or process to identify where gaps are and what differences exist between an organization's current situation and "what ought to be" in place' (Kim & Ji, 2018, p. 1). This kind of analysis explores the gap between where the situation is now to where it is desired to be in the future, thus revealing possible action points on how to get there. While generally applied to the marketing and communication industry (Kim & Ji, 2018), this study utilizes the same assessment structure to identify the gaps between the company's current processes and technology, and what they would need improve to enable the implementation of a DT.

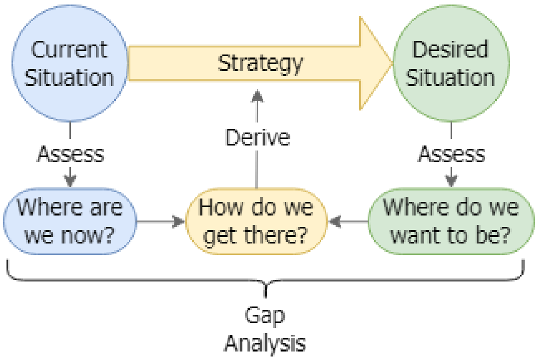


Figure 10: Gap Analysis Process (derived from Kim & Ji (2018))

This gap analysis process was translated to the goal-oriented process of developing a DTEA and deriving recommendations from it in Figure 11.

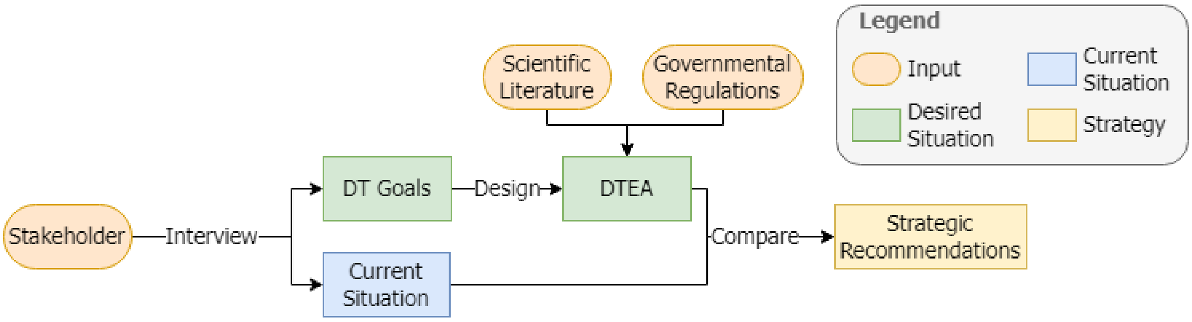


Figure 11: Gap Analysis to Develop Strategic Recommendations

First, stakeholder interviews are conducted to define the goals of the company for the DT, and their current situation. Based on the DT goals, the DTEA is designed using scientific literature and government regulations as input. Then, the current situation and the DTEA are compared to identify the gap and develop the strategic recommendations.

4.4 Conclusion

This chapter answered the first research question, and identified the elements to be considered when creating a DT for modular construction, and developed a process to derive recommendations for its implementation from these elements. It adapted the DT system architecture for modular construction by Pottachola et al. (2022) through the addition of a maintenance layer, thus creating a seven-layered architecture. The seven layers of the architecture include the physical layer, the data acquisition layer, the data transmission layer, the data storage and digital model/ information layer, the data analysis/ knowledge engine layer, the service layer, and the maintenance layer. Each of these layers has a distinct function that it needs to fulfil, and the layers need to be connected to each other to form a cyber-physical system. These functions include the collection, communication, storing, processing, and analysis of the data, as well as the intervention in the physical system and the evaluation of the digital system. Additionally, it was determined that stakeholders are crucial to the planning of sustainability-related DTs, and that there are different stakeholders affecting every layer, thus creating a stakeholder component. Further, to increase modularity and promote updateability, the digital components are split in the data that is needed for the DT to perform its functions, and the technology that is needed to facilitate the operations of the DT.

Based on the DT system architecture and the separation of each layer into three components, a DT element architecture (DTEA), which splits the DT system into its different elements that need to be considered in each layer. Based on this DTEA, a literature review about what contents need to be considered in each layer was conducted. The results of the literature review were summarized as questions related to each of the 25 elements in a descriptive version of the DTEA. This descriptive DTEA was created to guide the planning of a DT and help the user of the DTEA address all important components.

Lastly, the chapter addressed how to develop recommendations for the implementation of a DT in a company. It was determined to use a goal-oriented process based on the goals of the company. Then, a process for the development of DT Implementation Recommendations was defined based on the concept of a gap analysis. The process uses a combination of stakeholder, authoritative, and scientific information to define the desired situation, and then reiterates the information through another stakeholder interview to clarify the findings and assess the 'gaps' to the current situation. The findings are then used to formulate recommendations for the company.

5 Sustainability Goals and Related Processes at GWH

This chapter aims to answer the second research question:

> *What sustainability goals does GWH have and what activities they conduct contain decisions that have an influence on these sustainability goals?*

Thus, it will identify the sustainability goals of GWH and the processes within their company that might influence these goals. An important aspect of sustainable decision-making is defining the interpretation of sustainability considered. The research gap showed that aligning sustainability goals with stakeholder priorities makes sustainability more prevalent. Consequently, the sustainability goals of GWH will guide the interpretation of sustainability considered in the case study. Further, it is important that a sustainable decision-making process has an influence the sustainability. To only direct DTs to processes that can influence the sustainability, the processes able to influence the sustainability goals are identified. The process of identifying the sustainability goals and related processes is described in section 3.2.2.2.

5.1 Sustainability Goals and Scope

To conduct the case study, it is important to know what the company considers as its goals regarding sustainability. The sustainability goals of GWH were identified through interviews, the results of which are summarized in Table 5.

Table 5: Sustainability Goals of GWH

Sustainability Factor	Parameter Measured	Goal
Circularity	BCI	Current BCI assessed at 0.8, this value is assessed every few years, aim to hold or improve this value.
CO_2 Emissions	Net CO_2 Emissions	Carbon emissions not currently measured, should be measured to prove CO_2 neutrality.

As a company, GWH has two aims towards sustainability, (1) to produce the most circular building in the Netherlands, and (2) to have a CO_2-neutral building and construction process. Consequently, the circularity and CO_2 emissions were seen as the sustainability factors that the company currently considers. The circularity was measured using the Building Circularity Index (BCI), which is evaluated through the methodology followed by Alba Concepts. It assesses the circularity of a building as a percentage between 0 (0%) and 1 (100%), with 1 signifying a fully circular building (BCI Gebouw, n.d.). Their design was previously assessed at a BCI of 0.8, a score they wanted to maintain or improve on in future assessments. Secondly, they advertise that they want to 'go for completely CO_2 neutral in all choices' (geWOONhout, n.d.). On that account, they aimed for their production's CO_2 emissions to be zero. While they were looking to further advertise on CO_2 neutrality, they do not currently measure their emissions, and are not able to prove that their production is CO_2 neutral. Consequently, they would like to assess this aspect in the future.

Based on these goals, the sustainability scope will consider any DTs that aim at measuring or improving the circularity of the houses and production process or aim at measuring or reducing the CO_2 emissions of the houses and production process. Further, these impacts should have a direct influence on these factors.

5.2 Sustainability-Related Processes of GWH

Koldewey et al. (2020) highlight the importance of integrating any digital service into the existing business structure, to ensure a successful business model. VanDerHorn and Mahadevan expand on this and determine that to align the processes and the design of a DT, 'these processes, the information exchange and the decision-making points in the process need to be identified' (2021, p. 8). Next to identifying the processes in general, it is also important to distinguish the processes that have the potential to influence the sustainability aspects established in the last section. Consequently, this section will first identify the processes of GWH, and then identify which processes have the potential to impact the sustainability scope.

5.2.1 Process Structure of GWH

Five major phases of their business processes were identified, (1) product development, (2) project management, (3) engineering, (4) production, and (5) transport. Within these five phases, 19 disparate activities were distinguished as shown in Figure 12.

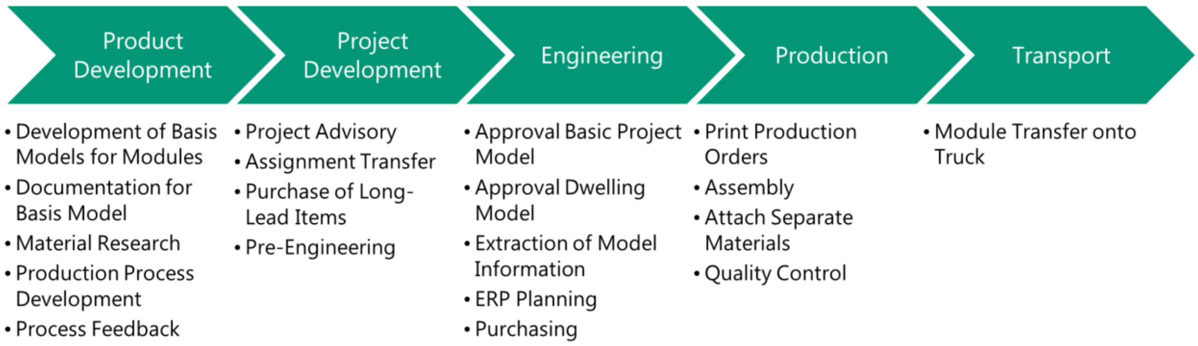


Figure 12: Processes in the Current Business Structure of GWH

5.2.2 Relation of Processes to the Sustainability Scope

Not all processes have the chance to influence the sustainability goals through decisions made in them, either because none of their decisions are able to influence the sustainability parameters, or because no decisions were identified in the process. This corresponds to the interviewees statements hinting that few decisions are made after the model is approved.

> *"Mostly we do not make any decisions, because [we] have already made the decisions in the pre-engineering phase, [...] sometimes there is a decision to change little things, [...] but mostly all things are known" (Project coordinator, personal communication, 20/09/2022)*

> *"If the models are correct, we say 'go', which means we start the process to generate the files and ERP information, start purchasing the materials [...]. From that moment we should not change anything anymore. (ERP integrator, personal communication, 14/09/2022)*

Consequently, some processes were excluded from further consideration in the case study. The decision on the inclusion of different processes is summarized in Table 6. Remarkably, it was found that most relevant decisions are part of the product and project development phases, as they decide on the materials and structure of the building. In the latter phases, decisions related to other aspects than the design were also considered, as they could influence the sustainability through e.g. equipment use, energy use, and logistics.

Table 6: Processes Included in the Case Study

Phase	Process	Decisions	Inclusion
Product Development	Development of Models for Basic Modules	Material Choices	Yes
	Documentation for Basic Module	Documentation process	Yes
	Material Research	Material choices	Yes
	Production Process Development	Production process changes	Yes
	Process Feedback	Decision to make changes to specific process or material	Yes
Project Development	Project Advisory	Façade material, client-based adjustments, site-based adjustments	Yes
	Assignment Transfer	-	No
	Identify Long-Lead Items	Deliverability of Items	No
	Pre-Engineering	Material specifications and suppliers	Yes
Engineering	Approval Basic Project Model	Approval	No
	Approval Dwelling Model	Approval	No
	Extraction of Model Information	-	No
	ERP Planning	-	No
	Purchasing	Long-term partners, identifying long-lead items	Yes
Production	Print Production Orders	-	No
	Assembly	Timing of production, equipment uses	Yes
	Attach Separate Materials	-	No
	Quality Control	Quality Control Criteria	No
Transport	Module Transfer onto Truck	Transport Order	No

5.3 Conclusion

This chapter addresses the second research question, and consequently identified the sustainability goals of GWH, and the activities they conduct that influence these goals. It was found that regarding its sustainability goals, GWH was mainly focused on the circularity and CO_2 emissions of their products. In the business structure, 19 activities were identified over the five phases of business processes. These five phases include the product development, the project development, the engineering, the production, and the transport. Based the information on decisions made in these phases, the processes to be included in the further research for the case study were determined. The results showed that most decisions affecting the sustainability goals of GWH were in the product and project development phases, with only one process selected in the engineering and production phase. Based on the findings in this chapter, nine processes of GWH will be considered for the DT Uses Framework.

6 DT Uses Selection for the Case Study

This chapter aims at answering the third research question:

> *What DT applications could support sustainable decision-making related to these processes and how can they be prioritized for the case study?*

This chapter reviews scientific research to identify potential DT uses and then select those most suitable for the case study. The method for this process is explained in the methodology in Section 3.2.2.3. Consequently, this chapter will first assess the interests and goals of the company, then select a list of potential DT uses, review them to create their DT Uses Templates, and lastly evaluate their suitability for the case study through a focus group.

6.1 Current Issues and Future Development Goals of GWH

This section presents the current issues and possible future developments of GWH that could be solved or facilitated through technologies according to key stakeholders of GWH.

6.1.1 Current Issues

There were three major topics that emerged from the experts when questioned about current issues they were facing in their processes, (1) inefficient feedback process and quality control, (2) inaccuracy of digital models, and (3) need for improvements to the production process to improve efficiency. The inefficiency in the feedback and communication processes were mainly mentioned related to the product development. As such, there was too little communication of feedback, between different processes in the company itself, but also related to the contractors constructing the houses on-site (Product coordinator, personal communication, 04/10/2022). Further, when changes were made the communication of these changes was improperly conducted, and would cause the production to slow down and create delays or quality issues in the process (Product coordinator, personal communication, 04/10/2022). As there were too little quality controls, and the quality controls that were conducted were not standardized enough, there were issues regarding quality assurance throughout the production process (Product coordinator, personal communication, 04/10/2022). Thus, creating a more efficient process for recording and communicating feedback was suggested (Product coordinator, personal communication, 04/10/2022). Further, there were complaints about the quality of the digital models of their modules, which contained 'many errors' (ERP integrator, personal communication, 14/09/2022). This would cause delays in the production and increase waste, as some products that were needed were not in the model and thus not ordered for production, and some that were included and ordered were not needed (ERP integrator, personal communication, 14/09/2022). Lastly, GWH would aim to increase the production output of their current operations, thus they saw a pressing need to increase the efficiency of the production line to match their expectations (Director GWH, personal communication, 15/09/2022). Similarly, there was a need to make the production process more efficient and create a better overview of the processes that a worker needs to complete to enable a more efficient process (Product coordinator, personal communication, 04/10/2022).

6.1.2 Future Development Goals

For their future development, the company had several goals as to where their processes are headed. A general goal was an increased standardization of their processes (Director GWH, personal communication, 15/09/2022). But they also knew that 'there is a lot of unknown to the wooden houses that we still run into when talking to clients or authorities' (Director GWH, personal communication, 15/09/2022). Consequently, monitoring and documenting any unknown aspects of wooden houses would yield benefits. These were seen in the monitoring of indoor air quality, indoor humidity, sound, and energy use (Director GWH, personal communication, 15/09/2022; Project coordinator, personal communication, 25/10/2022). Especially related to energy use, they also expected a development towards more clients to asking for net zero energy buildings (NZEBs) (Project coordinator, personal communication, 25/10/2022). In that regard, they are also interested in the energy consumption optimization of their installations, and connecting the information to sensor data from their air quality monitoring (Project coordinator, personal communication, 25/10/2022). Further goals were related to creating a basis for sustainable decision making, for example through assessing the environmental impact of houses and making further steps towards CO_2 neutral production (Project coordinator, personal communication, 25/10/2022). Another interest they had been working on was monitoring and reducing the waste produced during their production process (Project coordinator, personal communication, 04/11/2022). Their goal was focusing on further reduction of waste through design adjustments, and the recycling of waste streams (Project coordinator, personal communication, 04/11/2022). Next to goals related to monitoring or decision making itself, they also showed interest in expanding their products to include services after the production process (Director GWH, personal communication, 15/09/2022). Consequently, providing maintenance for a specified timeframe after the construction of the house was considered. Consequently, the decision was made to also consider the operational phase for such a DT use, as they would like to consider this specifically in the future.

6.1.3 Summary

Based on the interviews conducted the following issues and goals to aim DTs at were identified:

- Increasing the efficiency of the feedback communication and quality control processes;
- Increase the quality of the digital models;
- Improving the overview over the production process for the workers;
- Increasing the efficiency of the production processes;
- Monitoring unknown aspects of wooden construction (e.g. indoor air quality, indoor humidity, sound, and energy use);
- Supporting the development of NZEBs;
- Supporting the development of a CO_2-neutral production process;
- Monitoring and reducing the waste production;
- Expanding the offered products to services regarding the maintenance and operation of buildings in the future.

6.2 Sustainability-Related Potential DT Uses for GWH

The following section explores the potential DT uses considered for the case study. As described in the methodology in Section 3.2.2.3 (Step 2), the potential DT uses were identified by selecting scientific literature providing relevant insights into possibilities for DT application, and then selecting any DT applications that fulfill the sustainability, interest, and feasibility criteria. The selected DT uses were then sorted into the DT Uses Framework. Next, these potential DT uses are reviewed regarding their characteristics.

The nine DT uses found in scientific literature that fit the selection criteria, and the resulting DT Uses Framework for the potential DT uses for GWH is presented in Table 7. The next sections will conduct a literature review of each potential DT use, and summarize the gathered information through their DT Uses Template.

Table 7: DT Uses Framework GWH

Phase	Key Activities	Historical Analysis	Simulate/ Mimic	Extract/ Monitor	Predict	Orchestrate
Product Design	Development of Models for Basic Modules		Automated Multi-Parameter Design Optimization		Calibrated Building Energy Simulation	
	Documentation for Basic Module	Building Energy Benchmarking	Automated Sustainability Rating Scheme	Automatic Material Passport Generation		
	Material Research		BIM-based Life Cycle Assessment			
			BIM-based Building Circularity Assessment			
	Process Feedback					
Project Management	Project Advisory					
	Pre-Engineering					
Engineering	Purchasing					
Production	Assembly				Assembly Equipment Energy Management	
Operation	Use Phase					Sustainable Indoor Environmental Quality Optimization

The DT Uses Templates present an IS Architecture for each potential DT use. Figure 13 presents the legend used for all IS Architectures included in these DT Uses Templates.

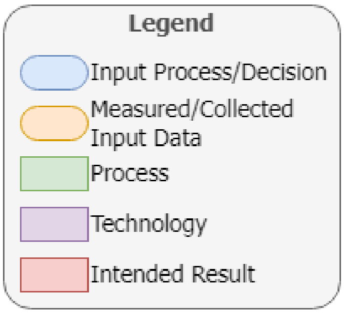


Figure 13: Legend for Generic IS Architectures

6.2.1 Automated Multi-Parameter Building Design Optimization

Using a multi-objective optimization approach, this DT use aims to find the optimal design solution while considering trade-offs between different parameters (Kheiri, 2018; Liu et al., 2015). According to Arora (2015), conducting an optimization means 'finding the best solution among many feasible solutions' (p. 1), where a feasible solution is any solution that fits within the predetermined constraints of the optimization. A multi-objective optimization requires the simultaneous optimization of two or more parameters (Arora, 2015), which results in a more realistic approach to an optimal design (Liu et al., 2015). Especially, when considering that changing one element of the building during the optimization process might influence other elements in return (Kheiri, 2018; Liu et al., 2015).

Previous studies in multi-parameter optimization have considered a range of parameters related to building design, and especially those related to sustainability (Karatas & El-Rayes, 2015; Kheiri, 2018; Liu et al., 2015; Najjar et al., 2019). Further, they showed that the methodology improves the quality of the building design. Additionally, this method is capable of considering non-sustainability-related criteria in the assessment and weigh them against sustainability-related criteria. As such, the consideration of energy efficiency/consumption parameters is a common occurrence in the research literature. As such, Najjar et al. (2019) consider the optimal design of a building to maximize energy efficiency, while minimizing the lifecycle cost and environmental impact. Similarly, Azari et al. (2016) analyzes the optimization of different life cycle impact parameters in cooperation with the operational energy use. In another paper, Harkouss et al. (2018) research the trade-offs between thermal and electrical demands, and life cycle costs for the design of the optimal net-zero energy building. Other sustainability-related aspects considered for multi-objective optimization are life cycle cost and CO_2 emissions (Liu et al., 2015; Xue et al., 2022), and the three dimensions of sustainability (Karatas & El-Rayes, 2015). All studies reviewed for this research concluded that this method helped them optimize the design and find valuable decision-making advice.

There is no unanimous approach to the multi-objective optimization process for buildings in scientific literature. However, there are different elements that are present in most studies, these are (1) the selection of parameters to guide the optimization, (2) the selection of an optimization algorithm or method, (3) an initial design, (4) alternative designs that are manually or automatically developed, (5) the evaluation of the parameters for each design, (6) the (automated) selection of pareto-optimal solutions (Azari et al., 2016; Karatas & El-Rayes, 2015; Liu et al., 2015; Xue et al., 2022). Several studies then proceed to a decision-making process to decide on the optimal solution for their purposes (Azari et al., 2016; Xue et al., 2022).

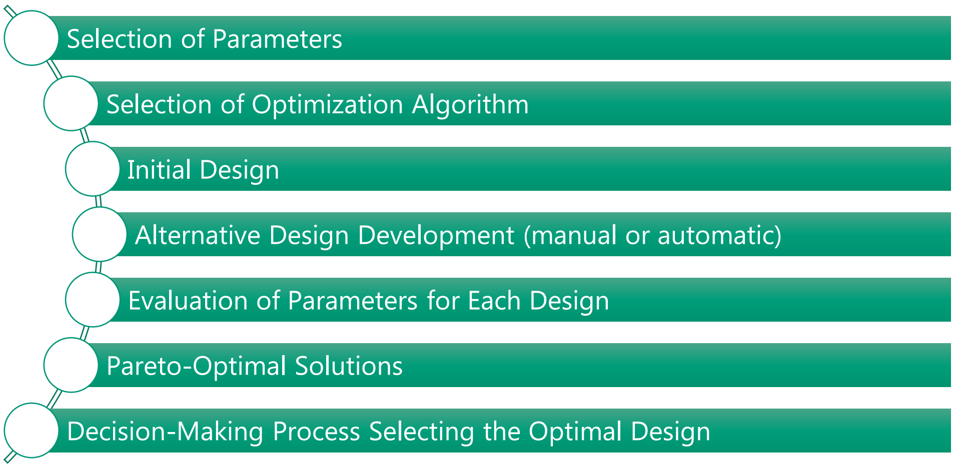


Figure 14: Elements of Performing a Multi-Parameter Optimization

In general, there are many benefits that can be connected to the use of a multi-objective optimization. On the one hand, it can help with decision making (e.g. for material decisions), provide near optimal solutions to complex problems, optimize building performance, and raise the overall quality of the building design (Karatas & El-Rayes, 2015; Liu et al., 2015; Najjar et al., 2019; Xue et al., 2022). On the other hand, this method can explore the design alternatives, and support the development of optimal solutions based on the local, on-site conditions, and investigate the relations between different parameters considered (Kang et al., 2018). However, these benefits require a DT that is able to suggest new alternatives, i.e. through parametric design (Xue et al., 2022). Further, an optimal solution often lies in the eye of the beholder, consequently the criteria, their assessment and the decision-making methodology should be created to reflect the priorities and needs of the decision-maker and/or client

(Harkouss et al., 2018; Karatas & El-Rayes, 2015). This can be achieved through the application of weights to the criteria used in the evaluation (Azari et al., 2016; Liu et al., 2015). While most optimizations for building design are still conducted manually, there are several suggestions that automating the process would be an interesting direction for the future research in this field that would become possible once interoperability issues are eliminated (Azari et al., 2016; Kheiri, 2018). First attempts at automating the assessment utilize BIM and other calculation tools to assess the different factors, and concluded they reduce the time needed for the assessments (Kang et al., 2018; Liu et al., 2015).

Table 8: DT Use Template - Automated Multi-Parameter Design Optimization

1 – Automated Multi-Parameter Design Optimization

General Details	*DT Use Name*	Automated Multi-Parameter Design Optimization
	DT Use Category	Simulate/Mimic
	Applicable MC Lifecycle Phase(s)	Product Design
	Applicable Key Activities	Development of Models for Basic Modules
Description	The use of an automated multi-objective optimization process with parameters related to building performance and sustainability to identify a range of optimized solutions and aid design decision-making.	
Process	First, decisions on the (sustainability-related) parameters for the assessments and the optimization method have to be made. Further, an initial design has to be developed and several alternative solutions have to be either manually created, or automatically produced, i.e. through parametric modelling or the creation of a predefined solution-space. Then, an automated framework for the assessment of the chosen parameters has to be created, that enables the evaluation of each parameter for every design alternative. Next, the optimization algorithm will identify a number of pareto-optimal solutions that will be considered for further assessment. Lastly, the decision-maker has to perform a decision-making process to identify the optimal design alternative.	
Potential Value	○ Reduce time needed for assessment of different designs; ○ Better design quality; ○ Improve basis for decision-making.	
Data and Information Needs	○ (Parametric) building designs; ○ Data needed for the evaluation of the chosen parameters for each design; ○ Evaluation method(s) for chosen parameters; ○ Preferences for decision-making.	
Software and Hardware Resources	○ Software to carry the information models that contain the necessary data from the design to determine the parameters; ○ Software necessary to simulate/calculate the chosen parameters.	
Important Competencies	○ Knowledge about what information the design model needs to be able to evaluate all parameters; ○ Domain specific knowledge about how to assess different parameters; ○ Ability to run the necessary software.	

1 – Automated Multi-Parameter Design Optimization

Generic IS Architecture

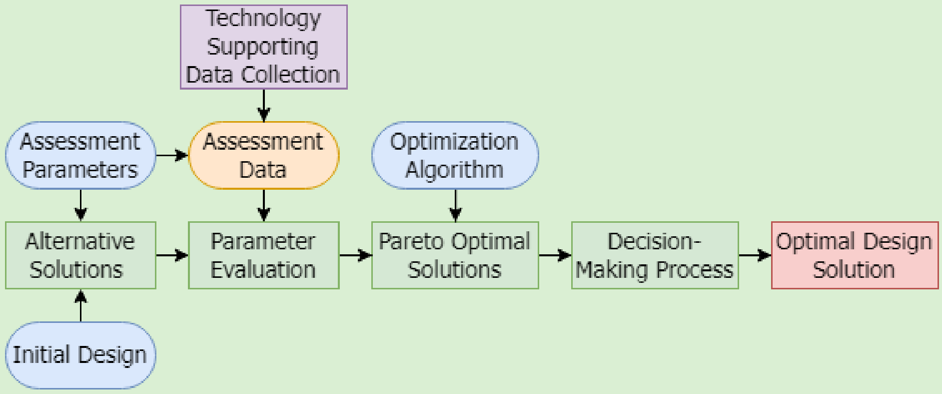


Figure 15: Generic IS Architecture – Automated Multi-Parameter Design Optimization

6.2.2 Building Energy Benchmarking

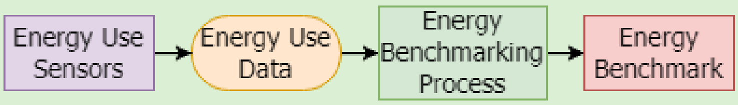
Energy consumption monitoring and management is a large topic for sustainability and smart cities (Francisco et al., 2020). Bortolini et al. (2022) reflect on the use of digital twins to conduct energy benchmarking and find that it is still a novel application that shows potential for improving energy use efficiency. Energy benchmarking can help to classify building energy efficiency and identify highly energy-efficient buildings. It also aids in the attempts to reduce the 'performance gap', which stands for the difference between the simulated energy use and the actual energy use of a building (Jafari et al., 2020). Nevertheless, the traditional way of energy benchmarking is rarely able to gather in-depth insights about where to start with improving this performance, as they rely on yearly averages of a building's energy consumption. Francisco et al. (2020) developed a methodology for energy benchmarking based on continuous energy consumption sensors, that provides a temporally segmented analysis for energy benchmarks. Therefore, it allows identifying the differences in performance between different times of the year or day. As such, they used energy consumption data and normalized it to reflect the influence of independent variables that would affect the energy consumption, such as the floor area, the number of occupants or the building age. Based on this efficiency score they then created a temporally segregated benchmark for each building. Creating energy benchmarks based on the detailed data gathered from sensors in the houses enables a more in-depth analysis for prognosis, maintenance, and energy management (Francisco et al., 2020; Jafari et al., 2020). Further, segregating the data into more specific benchmarks helps to identify and prioritize different energy efficiency improvement measures (Francisco et al., 2020).

Table 9: DT Use Template - Building Energy Benchmarking

2 – Building Energy Benchmarking

General Details	*DT Use Name*	Building Energy Benchmarking
	DT Use Category	Historical Analysis
	Applicable MC Lifecycle Phase(s)	Product Design
	Applicable Key Activities	Documentation for Basic Module
Description	The energy use of inhabited buildings is analyzed to assess the energy consumption over their lifetime/different periods, and establish a benchmark for the building type.	
Process	The energy consumption data from the building is normalized against different independent variables. Then, the data is used to create a profile of the energy use at different periods in time. The resulting profiles are visualized and analyzed.	

2 – Building Energy Benchmarking

Potential Value	o Allowing for a new depth of understanding building energy consumption and energy efficiency; o Detecting failure and supporting predictive maintenance; o Comparing different building designs based on energy performance; o Detecting the performance gap; o Consideration of temporal differences in energy consumption; o Identifying and prioritizing energy efficiency measures.
Data and Information Needs	o Continuous energy consumption data; o Optional: Other building related characteristics for normalization.
Software and Hardware Resources	o Sensors for energy consumption; o Data analysis software; o Software with the ability to visualize the results.
Important Competencies	o Data analysis and interpretation of the results.
Generic IS Architecture	 *Figure 16: Generic IS Architecture - Energy Benchmarking*

6.2.3 Automated Sustainability Rating Scheme

Sustainability rating schemes are increasingly being used to assess building sustainability, as they simplify the assessment from the comprehensive LCA process and allow the inclusion of other aspects of the building quality through a parameter-based system (Růžička et al., 2022). However, despite the simplified assessment, the rating schemes are still complex due to the variety of rating systems and criteria, which presents a challenge for automation. Despite the challenge, automating these rating systems assists design teams in improving the building quality and certifying projects with fewer resources (J. P. Carvalho et al., 2021). Commonly, the assessments are conducted when the building design is already finished, yet automated assessments allow the parameters to be compared at early design stages and different approaches to sustainable design can be weighed against another (J. P. Carvalho et al., 2019). In order to automate the assessment and give the highest benefits to its user, the process should provide enough precision to support the design and optimization process, yet be replicable to different assessment methods with minimal effort (Růžička et al., 2022).

Previous studies on automated sustainability rating schemes have identified structured approaches for the implementation of these automated processes, however, none of them have yet achieved a fully automatic method that is able to assess all parameters of the scheme. Růžička et al. (2022) developed an automated process to assess buildings according to the SBToolCZ scheme Figure 17 assessing around 200 parameters, which amounts to 40% of all criteria needed. The other 60% of the criteria could have been integrated into the assessment, but would have required a manual data transfer from non-automated sources. In their approach, Růžička et al. (2022) used BIM software to create a digital model, and then transferred it into a calculation software using an IFC format, to determine the necessary parameters. On the other hand, (J. P. Carvalho et al., 2021) developed a three-tiered framework for assessing a building according to the SBToolPT-H scheme, which achieved the assessment of 24 out of its 25 criteria. 13 criteria could be assessed using BIM-derived data alone, yet for the other criteria additional software is needed (J. P. Carvalho et al., 2019, 2021). Their assessment framework is based on a BIM model, which incorporates the necessary parameters for all objects in its structure, and then exports the BIM model to other assessment tools to determine specific parameters (J. P. Carvalho et al., 2021). Additionally, they recommend using an application programming interface (API) to automate the extraction, adaption and links between spreadsheets and BIM.

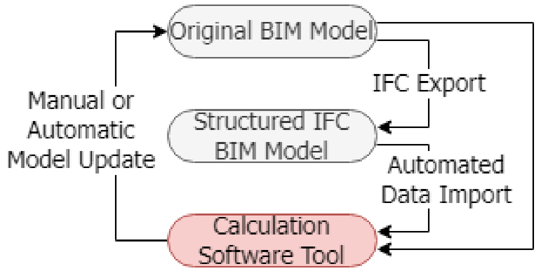


Figure 17: Automated Sustainability Rating Assessment (based on Růžička et al. (2022))

In general, an enormous challenge is arranging the assessment around the BIM software, as the data format and semantics of the assessment scheme have to be matched to the BIM data structure (J. P. Carvalho et al., 2019; Růžička et al., 2022). However, the BIM software is unable to conduct the assessment itself, thus needing to rely on connections to other software. Specific challenges are the need to conduct neighborhood modelling, the need to use GIS or Google Maps to assess accessibility criteria, as well as the need for an interface to manually insert LCIA values (J. P. Carvalho et al., 2021). Further, the assessment complexity in terms of the variety of parameters to be assessed also requires a wide range of data from various sources. Thus, the assessment needs access to BIM software, GIS, documents and technical reports, process descriptions, as well as other external sources to be conducted in full (Růžička et al., 2022). Further, the BIM model has to be of high quality to be able to support the assessment and provide the needed information, and should already be integrated into a company's processes to achieve maximum benefits (J. P. Carvalho et al., 2019, 2021). These benefits include a more accurate assessment based on the high data quality, the possibility of creating a personalized object library for the company, an increased efficiency in the assessment that requires less resources and time, and an uncomplicated process of sharing the information with stakeholders (J. P. Carvalho et al., 2020, 2021). Further, one can identify possible improvements to the building design with respect to the assessed parameters at an early stage, and thusly improve the overall quality of the building (J. P. Carvalho et al., 2020). As the schemes for sustainability ratings are often similar in nature, this structure could also be transferred to different schemes. In the long-term, it opens opportunities for the establishment of validated procedures and creating reliable and comparable criteria for the industry.

Table 10: DT Use Template - Automated Sustainability Rating Scheme

3 – Automated Sustainability Rating Scheme

General Details	*DT Use Name*	Automated Sustainability Rating Scheme
	DT Use Category	Simulate/Mimic
	Applicable MC Lifecycle Phase(s)	Product Design
	Applicable Key Activities	Documentation for Basic Module
Description	An automated process of collecting information from a BIM model, and connecting it to other software and calculation tools that assess the different criteria of sustainability rating schemes and aggregate their results.	
Process	The BIM model is used to gather relevant data from the building model, then the assessment is started, and the model is used to calculate different parameters, either directly in the BIM software, or through an API using an IFC export feeding other simulations. Additionally, neighborhood modelling is conducted to assess further	

<table>
<tr><td></td><td>parameters. The results for the different parameters are automatically collected and aggregated using an API to obtain the rating score.</td></tr>
<tr><td>Potential Value</td><td>

Fast and resource efficient assessment of building sustainability rating;
Higher assessment accuracy due to detailed modelling;
Support design decisions in the early development stages;
Higher overall building quality;
Opportunity to create comparable industry standards.
</td></tr>
<tr><td>Data and Information Needs</td><td>

High quality BIM model;
GIS/neighborhood model;
Other documents and information required to gather data for all parameters depending on the assessment criteria.
</td></tr>
<tr><td>Software and Hardware Resources</td><td>

BIM software;
GIS software;
Other software necessary to simulate and/or aggregate data for the assessment criteria.
</td></tr>
<tr><td>Important Competencies</td><td>

BIM modelling;
Neighborhood modelling;
Programming of APIs;
Competencies to use other necessary software.
</td></tr>
<tr><td>Generic IS Architecture</td><td>

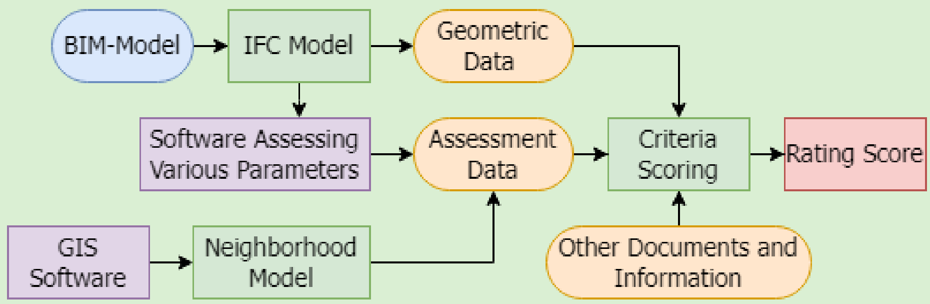


Figure 18: Generic IS Architecture - Automated Sustainability Rating Scheme
</td></tr>
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6.2.4 BIM-based LCA

A BIM-based LCA intends to integrate the process of assessing the environmental impact of a building through an LCA into the digital modelling process in a BIM environment (Wastiels & Decuypere, 2019). The rising need to consider environmental impacts already in the design stage increases the need to connect both processes. In general, the process of BIM-LCA integration can be sectioned into six steps (Figure 19). The assessment is based on a digital BIM model and connects it to an LCA databased to acquire results (Wastiels & Decuypere, 2019). Wastiels & Decuypere (2019) analyzed the different available methods to integrate them, and distinguished two main strategies, (1) obtaining specific model data (i.e. geometric properties, quantities, material types, etc.) necessary for the LCA from the BIM model through an export, and using the data as input for calculations in an external LCA software, or (2) integrating the information into BIM as parameters in the software, and performing the calculation within the BIM environment. For the first strategy, they found that the transmission of model data to the external software can be conducted through a bill of quantities (BoQ), an IFC export, or a through a BIM viewer software. While most studies attempting to connect BIM and LCA require manual or semiautomatic data transfers, some show automatic data transfer capabilities, which can simplify the assessment (Potrč Obrecht et al., 2020).

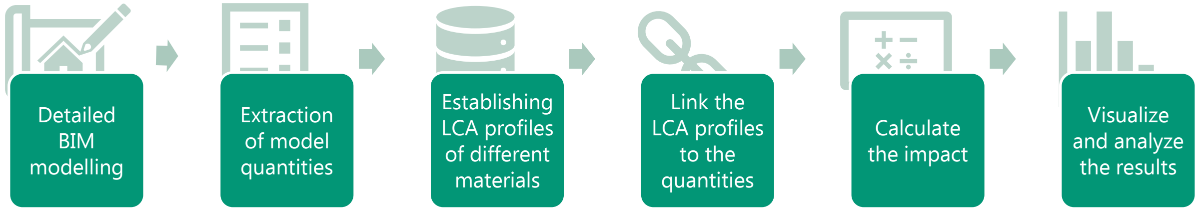


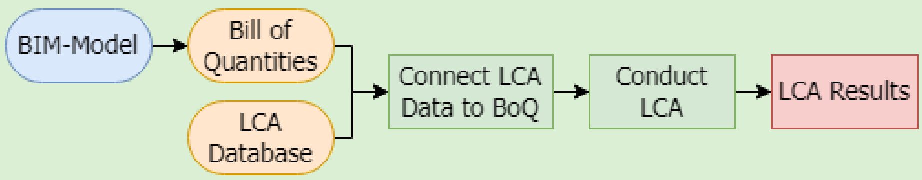
Figure 19: BIM - LCA Integration Process (based on Wastiels & Decuypere (2019))

Different examples of integrating BIM and LCA have been studied in scientific literature. Hollberg et al. (2020) used the BoQ of the BIM model to transfer information into a Dynamo script connected to an LCA database, and then manually reinserted the results into the BIM model for visualization. They compared the changes in the LCA results in weekly intervals by analyzing documents of a past design process, and then compare the preliminary assessments to the final design. They conclude that the simplifications made during the design process cause an extreme discrepancy between the design calculations and the final calculations, but the results could be improved by using predefined materials. In another study, Bueno and Fabricio (2018) compare the use of the BIM plug-in tool Tally to the professional LCA software GaBi based on the calculating the emissions of exterior wall segments from different materials. They found that while both results were in the same magnitude, the values differed significantly. They concluded that the discrepancies were partly due to modelling simplifications, but also ascribed them to differences in system boundaries and the use of a generalized database in the plug-in. In a different approach, Kaewunruen et al. (2020) also used a BoQ approach to gather the BIM model data and connect them to different emission factors per material. Then, they calculated the impacts in every life cycle phase using quantity-based formulas for different renovation measures. They concluded that the results were of 'acceptable accuracy' (2020, p. 14) but did not prove this conclusion through a statistical assessment.

The main criticism of BIM-based LCAs was a lack of accuracy in the results (Bueno & Fabricio, 2018; Hollberg et al., 2020; Potrč Obrecht et al., 2020). The roots of the inaccuracies were seen in simplifications and assumptions during the design stage, and the limitations of LCA databases that use generic data (Bueno & Fabricio, 2018). Thus, recommendations to improve the accuracy of the results include using pre-defined materials and objects to reduce assumptions and use machine learning tools to improve the remaining assumptions (Hollberg et al., 2020). Further, the BIM model and LCA methods need to have a higher degree of interoperability, and a specific BIM-oriented database for the assessment should be established (Potrč Obrecht et al., 2020). Despite the challenges experienced, the method was still seen as a possibility to guide designers, because it can already be applied in the design stage to assist them with more environmentally conscious decisions (Bueno & Fabricio, 2018; Kaewunruen et al., 2020). Even more so because it has a potential to increase design efficiency, to reduce errors in the project process, and to offer a platform to visualize the results to stakeholders (Kaewunruen et al., 2020).

Table 11: DT Use Template - BIM-based Life Cycle Assessment

4 – BIM-based Life Cycle Assessment		
General Details	*DT Use Name*	BIM-based Life Cycle Assessment
	DT Use Category	Simulate/Mimic
	Applicable MC Lifecycle Phase(s)	Product Design
	Applicable Key Activities	Material Research
Description	The integration of BIM and LCA, by connecting an LCA database to the BIM model quantities and using it to calculate the building impacts.	

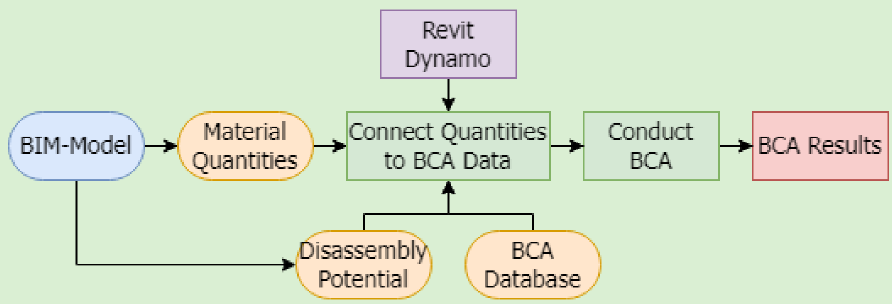
4 – BIM-based Life Cycle Assessment	
Process	The DT requires the creation of a detailed BIM model, from which the model quantities can be derived. These quantities are then (semi-)automatically connected to an LCA database, which contains assessment data for all materials in the model. The assessment results are then automatically aggregated and visualized to analyze them further.
Potential Value	○ Faster assessment process; ○ Early application to reduce environmental impacts in the design stage; ○ Increased design efficiency; ○ Platform to visualize results and present them to stakeholders.
Data and Information Needs	○ LCA Database; ○ High quality BIM-model in the design stage.
Software and Hardware Resources	○ BIM software; ○ LCA software or plug-in.
Important Competencies	○ BIM modelling; ○ Ability to analyze and interpret the LCA results; ○ Automation of data transfer processes.
Generic IS Architecture	 *Figure 20: Generic IS Architecture - BIM-based Life Cycle Assessment*

6.2.5 Automated Building Circularity Assessment

A building circularity assessment (BCA) helps to reflect on the circularity of design processes and buildings (Zhai, 2020). Assessing the BCA during the design stages can help designers to track the circularity of their design options and provide a basis for decision making towards a circular economy (Zhai, 2020). Similar to an LCA, assessing the building circularity requires large amounts of data that are traditionally connected to the building elements through manual processes. Thus, automating this process and connecting the assessment to BIM can increase the efficiency of the process (Zhai, 2020). There are different ways of connecting a BCA to BIM, either through exporting model information to a BCA software using a data exchange standard, or through establishing model parameters containing the necessary data, or through connecting the BIM model to a BCA database directly (Zhai, 2020). Göswein et al. (22022) developed a database-based assessment tool that uses a BIM model as input for the calculation of the BCA. First, the BIM model is used to identify and quantify the elements and parts in the building, then their Uniclass classifications are used to link them to relevant data contained in the database. This data and the BIM model are then used to calculate the circularity indicators, which are finally combined in a circularity report for the building. While this method integrates BIM and BCA, the assessment tool still requires manual steps during the assessment. In another study, Zhai (2020) developed a methodology for integrating the BCA in the BIM software using Autodesk Revit and Dynamo, which completely automates the assessment. The Dynamo model is used to extract the information from the BIM model, connect it to an external database, and conduct the assessment within the Revit software. Further, the program allows the automatic visualization of the data in a 3D model. A major aspect of determining the circularity is assessing the disassembly potential of each component in the building (Göswein et al., 2022; Zhai, 2020). Göswein et al. (2022) assesses this aspect in an additional step to the process, while Zhai (2020) suggests including the disassembly potential as a parameter in the BIM model. The automation of BCA assessments using BIM allows the assessment of BCA metrics in the design stage and enables a 'more holistic approach to building circularity' (Göswein et al., 2022, p. 2). As such, it promotes integrating circularity aspects into the design considerations and allows the comparison if design alternatives based on circular metrics (Zhai, 2020).

Table 12: DT Use Template - Automated Building Circularity Assessment

5 – Automated Building Circularity Assessment

General Details	*DT Use Name*	Automated Building Circularity Assessment
	DT Use Category	Simulate/Mimic
	Applicable MC Lifecycle Phase(s)	Product Development
	Applicable Key Activities	Material Research
Description	Automated assessment of the circularity of a building through a BIM model and a connected Excel-based database.	
Process	The BIM model is used to gather the material quantities and disassembly potential of the elements, and links them to BCA database entries using a classification system. Collecting the information from the model and the database is automated using a Dynamo model in Revit. The data is combined to calculate the circularity metrics of each element and the building. The results are then compiled in the program and visualized in the BIM model.	
Potential Value	○ Resource and time-efficient assessment of building circularity; ○ Assessment of BCA in the design phase; ○ Comparison of design alternatives based on circular metrics; ○ Development of a holistic process towards building circularity.	
Data and Information Needs	○ BIM model including uniform classification of different elements and parts; ○ External BCA database containing relevant data for calculations; ○ Disassembly potential for the elements.	
Software and Hardware Resources	○ Autodesk Revit; ○ Autodesk Revit Dynamo; ○ Microsoft Excel; ○ External Database (either link to existing one or create own database).	
Important Competencies	○ Modelling in Revit and Dynamo; ○ Data interpretation of results.	
Generic IS Architecture	 *Figure 21: Generic IS Architecture – Automated Building Circularity Assessment*	

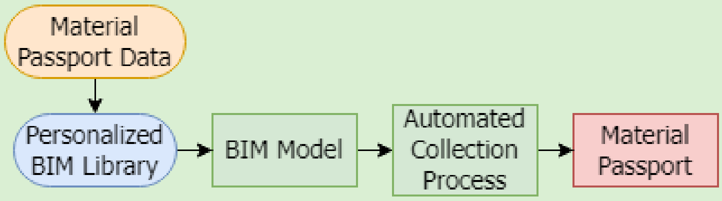
6.2.6 Automatic Material Passport Generation

A material passport (MP) is intended as a (digital) document containing information about a building and its materials, which can be given at different levels of detail depending on the intended use (Talla & McIlwaine, 2022). An MP can range from being a document about the composition of building materials to detailed data records including different things like its features, location, history, ownership, technical details and environmental characteristics (Atta et al., 2021; Honic et al., 2019; Talla & McIlwaine, 2022). Using BIM software, the process of compiling and expressing that data can be improved by using it as a data storage and sharing method (Atta et al., 2021). This could improve the considerations for different sustainability aspects during the design phase (Atta et al., 2021), and reduce the barriers for reusing materials at the end-of-life stage through providing information about the materials and their components (Talla & McIlwaine, 2022).

In scientific literature, Atta et al. (2021) created a methodology for a building-element-based MP to assist with building-level sustainability considerations. They included qualitative criteria, such as technical information, as well as guidelines for safety, circularity, and disassembly practices for stakeholders. Further, they assessed quantitative criteria related to the de-constructability, recovery, and environmental performance. They concluded that their MP was successful in providing information that can be used to make sustainability-based design decisions. In another study, Honic et al. (2019) created a building-level MP with semi-automatic compilation. They considered the material composition, mass of recyclable and waste materials, and environmental impact of the building. They concluded that the ability to create a MP semi-automatically was demonstrated, yet further automation would be challenging. The challenges they found relate to the lack of standards and regulations regarding MPs, the lack of consistent units and assessment methods in environmental databases, the necessary detail of information for the assessment, and the skills needed use different software and implement a specific BIM modelling methodology. However, once the MP is created, it can assist in making decisions about more sustainable building designs and optimize the environmental impact of a building (Atta et al., 2021; Honic et al., 2019). Further, it could help to evaluate the value and usability of materials at different stages of their lifecycle, optimize a building's recycling potential, and increase the demand for recycled materials (Honic et al., 2019; Talla & McIlwaine, 2022).

Table 13: DT Use Template - Automatic Material Passport Generation

6 – Automatic Material Passport Generation		
General Details	*DT Use Name*	Automatic Material Passport Generation
	DT Use Category	Extract/Monitor
	Applicable MC Lifecycle Phase(s)	Product Development
	Applicable Key Activities	Documentation of Basic Module
Description	Automatic generation of a MP that collects a range of data and information about the building and its elements.	
Process	The data needed for different aspects of the material passport is added to the BIM environment for each building element, and then extracted for the documentation of the building based on the combined information of the elements included in the design.	
Potential Value	o Assistance for sustainable decision-making; o Assessment value and usability of building materials at their EoL; o Optimized recycling potential of buildings; o Possibility to increase the demand for recycled materials.	
Data and Information Needs	o BIM library including all used building elements; o Data on the different aspects relevant to the MP for all building elements.	
Software and Hardware Resources	o BIM software; o Other software necessary to gather the required data.	
Important Competencies	o BIM modelling; o Data interpretation.	

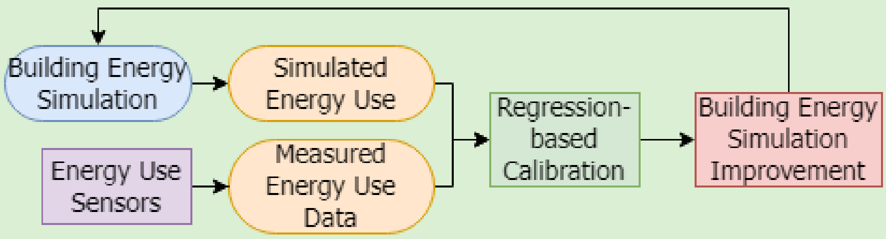
6 – Automatic Material Passport Generation	
Generic IS Architecture	 *Figure 22: Generic IS Architecture - Automatic Material Passport Generation*

6.2.7 Calibrated Building Energy Simulation

Newly constructed buildings in the Netherlands must meet the 'Nearly Energy-Neutral Building' (BENG) requirements (RVO, 2022). These requirements mandate the use of energy performance calculations to determine the BENG indicators. However, there is often a 'performance gap' between the predicted and the actual energy consumption of a building (Tronchin et al., 2018). This performance gap can influence both the economic and environmental performance estimations of the building. Most of this gap is related to the wide array of parameters influencing energy performance, numerical and modelling errors, and the lack of consideration for occupant behavior (Coakley et al., 2014; Tronchin et al., 2018). Calibrating energy simulations with performance data from the operational phase of buildings has been shown to reduce the discrepancy between performance and simulation, by adapting the predictions to the through operational profiles (Tronchin et al., 2018). Tronchin et al. (2018) showed a process of simulating building energy consumption and then performing a regression-based calibration every year to calibrate the model and compare it to next year's performance. In the third year of model comparison, the cumulative deviation of the model to the measured data had been reduced from over 4000 kWh/yr to less than 500 kWh/yr. While the concept has shown to work, Coakley et al. (2014) criticize a lack of standardization for the model development, and the lack of automation of the process, which requires user intervention in every step. Nevertheless, the method is beneficial to the accuracy of the simulations as it gives important information for the prediction. Further, it can detect critical assumptions made in the modelling process, and improve them through measured data.

Table 14: DT Use Template - Calibrated Building Energy Simulation

7 – Calibrated Building Energy Simulation		
General Details	*DT Use Name*	Calibrated Building Energy Simulation
	DT Use Category	Predict
	Applicable MC Lifecycle Phase(s)	Product Development
	Applicable Key Activities	Development of Models for Basic Modules
Description	Collecting energy use data from operational buildings and using it to calibrate the energy use simulations for new buildings.	
Process	The energy consumption of a building is measured using sensors. Then, the collected data is compared to the simulated energy consumption data for the building. Next, a regression-based calibration is conducted to adjust the simulation performance. From these adapted simulations, the predictions for future buildings can be adjusted.	
Potential Value	o Better environmental and economic performance estimation; o Increase the accuracy of energy use simulations; o Improve building performance prediction; o Detect critical assumptions in the modelling process.	
Data and Information Needs	o Simulated energy use data; o Measured energy use data.	

7 – Calibrated Building Energy Simulation	
Software and Hardware Resources	○ Energy consumption sensors; ○ Energy use simulation software; ○ Software to perform a regression-based calibration; ○ Data analysis software.
Important Competencies	○ Data analysis and interpretation; ○ Regression-based model calibration.
Generic IS Architecture	 *Figure 23: Generic IS Architecture - Calibrated Building Energy Simulation*

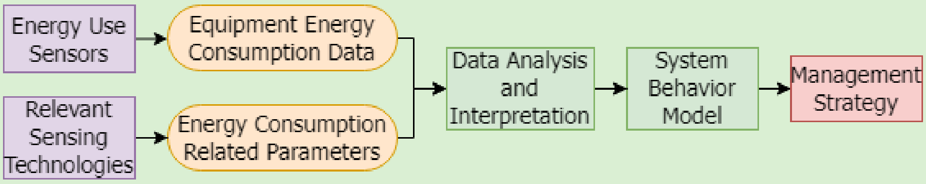
6.2.8 Assembly Equipment Energy Management

In a production line with electrical equipment, a DT can be established to monitor and optimize the energy consumption (EC) of the equipment (Zhang et al., 2022). Additionally, the use of real-time monitoring devices and continuous updates to the models have the potential to increase the benefits of these processes. Consequently, Zhang et al. (2022) created an equipment energy consumption monitoring system based on a DT. Through sensors on the equipment, they gather EC data, i.e. the consumption of electricity, lubricants and compressed air, as well as EC-related parameter data, such as machining parameters, workpiece parameters, tool parameters, scheduling parameters, and machine specifications. Based on this data, they create a highly detailed virtual models that can monitor the data, simulate and predict future EC, and test potential production processes. Finally, they identify three potential application areas for the DT, EC monitoring, EC analysis and EC optimization. The monitoring applications include the monitoring of the machine itself by comparing it to historical data, and the verification of predictive models through comparison to the monitored data. The analysis applications offer insight into the machine behavior, and the impact different parameters have on the EC. Lastly, the optimization applications can optimize parameter settings, scheduling and perform predictive maintenance. They conclude that the new EC management system can effectively reduce the energy consumption, and hence improve energy efficiency.

Table 15: DT Use Template - Assembly Equipment Energy Management

8 – Assembly Equipment Energy Management		
General Details	*DT Use Name*	Assembly Equipment Energy Management
	DT Use Category	Predict
	Applicable MC Lifecycle Phase(s)	Production
	Applicable Key Activities	Assembly
Description	The use of energy consumption data to monitor and analyze the current assembly processes and optimize their energy efficiency for the future.	
Process	The energy use data and other relevant energy consumption parameters are used to create a virtual model for the monitoring, simulation and prediction of the system behavior. These models can then be utilized for different applications that allow deeper insight into the results and can aid the management of the equipment.	
Potential Value	○ Monitoring energy consumption;	

8 – Assembly Equipment Energy Management

	○ Analysis of different aspects of the production and assembly processes ○ Optimized scheduling and machine parameters; ○ Performing predictive maintenance; ○ Improved energy efficiency of the production processes.
Data and Information Needs	○ Energy consumption data; ○ Energy consumption related parameters (depending on the intended use).
Software and Hardware Resources	○ Sensors to monitor energy consumption and other relevant parameters; ○ Modelling and simulation software for the processes; ○ Data analysis software.
Important Competencies	○ Data analysis and interpretation of the results.
Generic IS Architecture	 *Figure 24: Generic IS Architecture – Assembly Equipment Energy Management*

6.2.9 Sustainable Indoor Environmental Quality Optimization

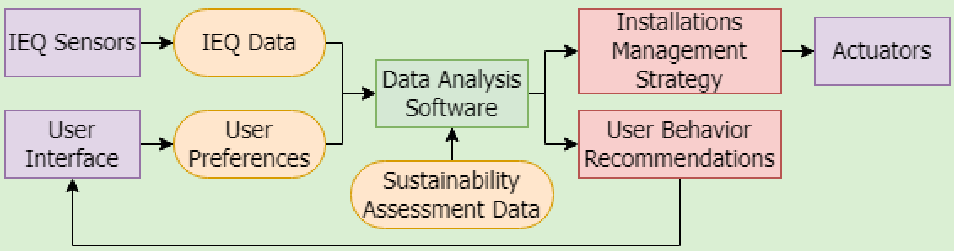
Sustainable indoor environmental quality (IEQ) optimization aims to optimize the environmental quality of a building, by integrating considerations for the sustainable operation and the occupant comfort. This presents an interdisciplinary approach to sustainability concepts that also includes stakeholder perspectives (Zaballos et al., 2020). Tagliabue et al. (2021) present a framework simultaneously assessing the sustainability of the building according to the LEEDS sustainability rating, and the IEQ based on environmental sensors. Information displays for the building's users present the buildings status for different parameters and make suggestions for sustainable actions the user can take. This aims to promote sustainable behavior to the users of the building. In another example of combining occupant comfort and sustainability assessments, Zaballos et al. (2020) created a DT that monitors IEQ data, as well as energy efficiency. Further, occupant preferences are collected through user interfaces, and used to adjust the parameters for the system. The system then employs actuators to adjust the building performance and recommends actions for the facility manager and occupants that would increase the occupant comfort and/or sustainability, while keeping the other parameters in check. Both DTs suggested are integrating data collected through sensors and user interfaces, and work with recommending actions for users to take, thus integrating stakeholders in different ways. This helps to involve users in sustainability efforts, and increases their sustainability knowledge (Zaballos et al., 2020). Further, it leads to improved occupant comfort and better building management (Tagliabue et al., 2021). Next to stakeholder involvement, the multi-disciplinary approach is seen as a way to motivate people to contribute to these common challenges (Zaballos et al., 2020).

Table 16: DT Use Template - Sustainable Indoor Environmental Quality Optimization

9 – Sustainable Indoor Environmental Quality Optimization

General Details	*DT Use Name*	Sustainable Indoor Environmental Quality Optimization
	DT Use Category	Orchestrate
	Applicable MC Lifecycle Phase(s)	Operation
	Applicable Key Activities	Use Phase

9 – Sustainable Indoor Environmental Quality Optimization

Description	Combining assessments of IEQ data, sustainability parameters, and user preference, to give recommendations for the management of different aspects of the building, such as lighting, temperature, etc.
Process	Sensors inside the building monitor IEQ data, while sensors and calculations can be used to assess different aspects of sustainability. Simultaneously, user preferences are collected through user interfaces. The DT then combines the different data streams collected to suggest or implement measures that improve occupant comfort and optimize the sustainability at the same time. The system can steer actuators to change the conditions of the building actively, and recommend actions for users or facility managers to improve the occupant comfort in the most sustainable way.
Potential Value	o Increased sustainability performance of the building; o Integration of users in sustainability efforts; o Increasing user knowledge about sustainability; o Improved occupant comfort and building management; o Multi-disciplinary approach.
Data and Information Needs	o IEQ monitoring data; o User preferences; o Sustainability assessment-related data; o Predictions on sustainability and impact on IEQ of recommended actions; o Decision-making processes to decide on actions and recommendations.
Software and Hardware Resources	o IEQ monitoring sensors; o Sensors and software to assess sustainability; o User interfaces; o Data analysis software; o Dashboard for the presentation of recommendations; o Actuators for different installations.
Important Competencies	o Data analysis and interpretation.
Generic IS Architecture	 *Figure 25: Generic IS Architecture – Sustainable Indoor Environmental Quality Optimization*

6.3 Evaluation Results

The focus group evaluation is transcribed in Appendix C: Evaluation of DT Uses Framework – Focus Group Transcript. The given ratings for the different DT uses are presented in Figure 26. The results show that three DT uses were estimated to have a perfect suitability score of nine. As only two DT uses were intended to be chosen, the interviewees were asked to prioritize the DT uses according to their preferences. This resulted in the Energy Benchmarking and BIM-based Life Cycle Assessment being chosen as DT uses for the case study.

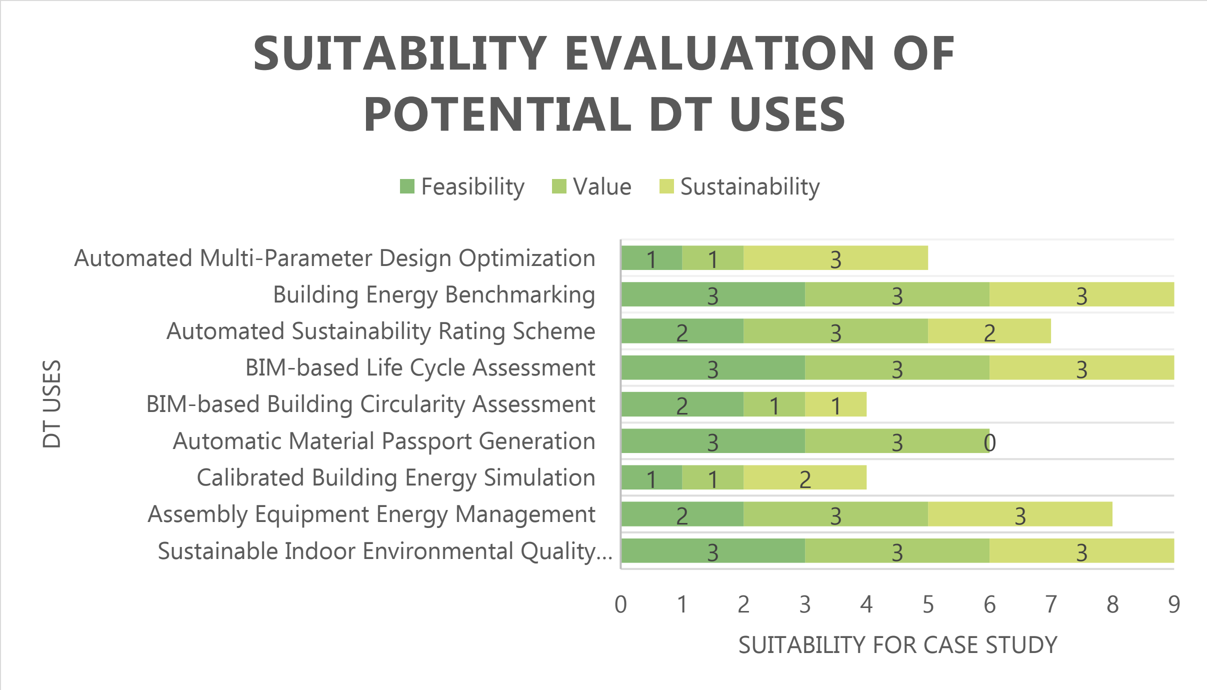


Figure 26: Suitability of Potential DT Uses for the Case Study

The automated multi-parameter design optimization was seen as highly influential to the sustainability of a project, as it was expected improve the design of a building on different levels. The participants mentioned possibilities of achieving 'more efficient space plans, more efficient facades, more efficient assembly, [and] less material use' (Project coordinator, personal communication, 07/11/2022). An acceptable score was given to the feasibility and value, as the decisions about the building design are often not only made by the company itself, but heavily influenced by the environment of the house and aesthetics. They specifically want to have 'some kind of freedom in the design' (Director GWH, personal communication, 07/11/2022), and 'give space to the architect to be quite aesthetical' (Project coordinator, personal communication, 07/11/2022). Thus, using a DT-based optimization might be difficult, as the freedom of design would be constricted too much. Further, they were concerned about the selection of parameters and their calibration, as it might 'take quite a lot of time and information to make these parameters' (Project coordinator, personal communication, 07/11/2022) and to decide on their importance and calibration. However, they suggested that this DT use was 'most interesting in the feedback loop' (Project coordinator, personal communication, 07/11/2022) to show what impact different decisions have on the performance for different parameters.

The building energy benchmarking was seen as a highly feasible, valuable and sustainability improving DT use. Specifically, it was considered highly feasible as it has a simple structure, and most data requirements are met through existing devices. Further, this DT use was considered helpful to assessing the energy usage and using it for future service contracts. While originally it was presented as a method to assess the energy usage of a complete house design, they indicated that the assessment of different installation setups for the houses would be especially valued, as there were still questions about their performance. This digital twin would enable them to identify the 'optimum in terms of comfort and energy usage' (Director GWH, personal communication, 07/11/2022). While discussing the value of the DT use, they also remarked that the value of the application itself would partly be directed to their clients, and they would also have indirect benefit from their interest in the assessment.

The automated sustainability rating was estimated to be acceptably valuable and moderately feasible. For one, it would provide commercial value, however, 'if it [were] used more in the whole construction industry, the commercial value [would] also be higher' (Project coordinator, personal communication, 07/11/2022). Further, they found that using it in tenders in the future might be a benefit, as they were able to use it as a 'difference compared to [their] competitors' (Project coordinator, personal communication, 07/11/2022). They further worried that they would not have the highly detailed information needed at that stage yet. However, this DT use would become more important if more clients ask for such schemes in the future. Next, the sustainability was considered moderately improved. They concluded that there might be a high potential, yet clients would not necessarily be convinced by it, thus limiting the potential impact. Especially in comparison with an LCA, the sustainability rating would have less importance, as LCAs are based on EU norms that are still lacking for sustainability rating schemes. Thus, the rating was seen as company dependent and not objectively meaningful.

The BIM-based LCA was seen as highly impactful for the sustainability of their projects, as clients are expected to be quite willing to change design decisions based on LCA results. Compared to sustainability rating schemes, clients 'understand and know how to interpret the life cycle assessment' (Director GWH, personal communication, 07/11/2022). Further, it was determined that the feasibility could be high if the assessment was integrated in the BIM program, for example through a plug-in that give immediate feedback on the impact of material changes. Then, it 'could support [them] within [their] processes, especially in the product development' (Project coordinator, personal communication, 07/11/2022). This would be supported by high-quality BIM models they have available. Further, the value of the DT was also estimated to be high, especially as federal CO_2 taxes have been in discussions in recent times, and it could assist with regulations regarding CO_2 and NO_x emissions. They further highlighted the importance of the assessment being automated, and the assessment method relating to the NMD, the content of which is recognized by the national government and maintained on a national level.

The BIM-based building circularity assessment was seen as 'moderate for the feasibility, when it is based on Excel, but […] high when it is a [BIM] plug-in' (Project coordinator, personal communication, 07/11/2022). It was finally set to moderately feasible, as all cases found for the implementation of automated BCAs used an Excel-based method, and information about a plug-in option not found. Further, the value and sustainability improvements were seen as acceptable, as there is currently no standardized way of assessing the circularity in the market. They commented that 'if there is no norm, you can't compare it and therefore the value is not really high' (Project coordinator, personal communication, 07/11/2022). Further, it would make the interpretation of the results more difficult. For the sustainability, it was remarked that without a norm to control it, 'life cycle assessment is a better way to approach it' (Director GWH, personal communication, 07/11/2022).

The automated material passport generation was considered to be very feasible, if it is integrated into the BIM software as a plug-in. Further, it would need to integrate the information structure of the NLSfB, which is also the standard for other systems in the Netherlands. The value of this is also considered to be high, as it is currently a requirement for different subsidy programs, and the requests for it are expected to increase in the near future. On the other hand, the sustainability improvement was seen as 'very low', as the material passport would not motivate sustainability improvements. Especially, as 'the quality of material passports [was] based on the amount of materials […], it also won't help with sustainable decision-making' (Project coordinator, personal communication, 07/11/2022). Further, the benefits of a material passport were seen as being directed towards the maintenance and end of life phases, thus not of help in the design phase.

The calibrated building energy simulation was estimated to have an acceptable feasibility as there would be a lack of staff capable and available to conduct the data analysis steps and relate the results back to performance optimizations. The value was also considered to be acceptable as the results were not considered to be useful for their current business model and better suited if the engineering were to differ more between projects. Especially the building energy benchmarking was seen as delivering a similar result to the energy benchmarking while having a higher resource intensity. Further, the sustainability was considered moderate, as it could be used for decisions in the future.

The assembly equipment energy management was seen as moderately suited for the application in the production line, as the factory only assembles the modules. Thus, the energy usage is already very limited and little optimization potential is expected in that regard. This might be more beneficial if more elements of the production are conducted on-site. Thus, readjusting the focus of this DT use to waste optimization was suggested. Through the detection of the waste origin, they expect to be able to contact suppliers and influence them to better fit their needs and thus reduce waste. This alternative use was considered to be moderately feasible, as the implementation will require a lot of additional effort. This would also present high value and sustainability improvements for the company, as it would allow them to reduce the costs and emissions of the production through waste reduction.

The sustainable indoor environmental quality optimization was considered to be highly feasible, as the company was already working to set up a system similar to it, which also motivated the installation of different sensors in their houses. Consequently, the monitoring data from sensors is widely available, as well as weather forecasting data. They are also working towards interpreting user preferences through a user interface in the houses. However, there would still be some difficulty in the organization and connection of the different systems, as it would require connecting the installations to the DT system. While the technology for this might be available, current installations software need to be severely changed for the set-up, which creates difficulties for the maintenance and reliability of the system. Hence, a cooperation between the installations manufacturer, the monitoring organizer, the contractor, and a maintenance company would be relevant for implementation in residential houses. Further, they found the availability of data analysts and managers to implement the resulting feedback into the designs critical for the success. The value of this DT use was also considered to be high, as it would provide a unique selling point for the houses that gives large commercial opportunities. Lastly, they estimated a high sustainability improvement, as the system would allow the optimization of the energy usage independent from the actual user behavior but could be increased through users cooperating with the system. Further, the expected improvement would depend on having an artificial intelligence with a high capacity for learning from user behavior and adjusting its algorithm accordingly.

Finally, the three highest rated potential DT uses were found to be (1) building energy benchmarking, (2) BIM-based LCA, and (3) sustainable indoor environmental quality optimization. As the goal for this research was to select two DT uses for case studies, the interviewees were asked to rank the three options based on their priorities. As a result, it was decided that the BIM-based LCA had the highest priority, as the company currently did not focus on this but felt its importance for the expected regulations regarding nitrogen and CO_2 emissions. Further, sustainable indoor environmental quality optimization was seen as having the lowest priority, as the research for this DT use was already fairly advanced and would not need as much additional attention. As a conclusion, it was decided to focus on the BIM-based LCA and building energy benchmarking for the further progression of this study.

1 Building Energy Benchmarking

2 BIM-Based LCA

3 Sustainable Indoor Environmental Quality Optimization

Figure 27: Ranking of DT Uses for the Case Study by GWH

6.4 Conclusion

This chapter addressed the third research question, and identified potential DT uses that can support sustainable decision-making and conducted an evaluation to prioritize them for the case study. Due to the large number of potential DT uses, criteria were developed to limit the selection to DTs of general interest to GWH that can support sustainable decision-making. Their interests were determined through interviews regarding their current issues and goals for further development. Based on the criteria, nine potential DT uses were identified with the DT Uses Framework, (1) building energy benchmarking, (2) automated multi-parameter design optimization, (3) automated sustainability rating scheme, (4) BIM-based LCA, (5) BIM-based BCA, (6) automatic material passport generation, (7) calibrated building energy simulation, (8) assembly equipment energy management, and (9) sustainable indoor environmental quality optimization. It was notable that most DT uses were found in the product design phase. Each of the potential DT uses were reviewed, and a DT Uses Template created.

The DT uses were then presented to stakeholders from GWH, where they evaluated their theoretical benefits based on the DT Uses Template. The evaluation was guided through criteria regarding the feasibility, usefulness, and sustainability impact of the potential DT uses to GWH. In the end, three potential DT uses were given the highest score, and the company was asked to prioritize the two that were of the highest importance to them for this study. This led to the selection of building energy benchmarking, and BIM-based LCA as the DT uses considered in the case study. The results of the evaluation showed that all of the potential DT uses were thought to bring some value to GWH, most were even thought to be highly valuable to them.

Next to the prioritization of the DT uses, the evaluation helped to identify two factors that have a large influence on the expected value and sustainability impact of DTs for companies, first the availability and level of government regulations, and secondly, the understanding and influence of the results on clients. In several of the DT uses presented to GWH, the lack or sub-optimal quality of government regulations and standardization were mentioned in relation to low value and sustainability impact for several DT uses. For example, the regulations for MPs were seen as qualitatively insufficient for the MPs to have an impact on sustainability. Further, the automated sustainability rating schemes and automated BCAs were seen as less valuable to GWH than an LCA, due to the lack of standardization which would allow comparison between companies and consequently support competitiveness. Similarly, the understanding of clients for the results of different sustainability assessments was seen as highly influential on the decision making. This was related to their power on the design decisions for the projects and products. They were considered to be more willing to change their design decisions when they understand the impact these decisions have and understand the assessment behind the decision-making. Consequently, the value and sustainability impact for GWH was not only related to internal factors and the design of the DT, but also to external factors that have to be addressed at a different level.

Another finding in this chapter, was that the feasibility of simpler, BIM-based DTs was often seen as more feasible than the more complex DTs with higher data collection, and maintenance needs. Further, the higher the control and power of the DT over design decisions, the less desired the DT was. The only exception to this being the sustainable indoor environmental quality optimization, the sensors for which were mostly available, and was already planned in the future development of GWH. Yet investing into DTs with high initial effort, or those with results that do not have potential for being marketed to clients seemed to provide less attraction.

7 Implementation of the DTEA to the GWH Case Study

This chapter answers the last sub-question in this study:

> *What strategic recommendations for the implementation of a DT for specific DT uses can be given to GWH?*

The last chapter selected the DT uses to be considered in this chapter, building energy benchmarking and BIM-based life cycle assessment. The goal is to develop strategic recommendations for implementing the two DT uses selected to answer the sub-question. Overall, each of the DTEAs will be developed using a design science approach (see Figure 6), following the process described in Section 3.2.2.4. The evaluation of the artefact (Step 5) is conducted in the next chapter. For confidentiality reasons, GWH was the only stakeholder providing input for the case study, any needs and interests of other stakeholders were assessed based on GWHs assertions.

7.1 Building Energy Benchmarking DT for GWH

The first part of the case study develops recommendations for GWH regarding the development of a DT for energy benchmarking (EB). This chapter reviews the process of creating an EB process, which is then used to design the DTEA. Further, it derives strategic recommendations from it using the process detailed in Figure 11. The process of this section follows the design science structure detailed in Figure 6. First, it analyzes the needs of the stakeholder to define the goals of the DT, from which the requirements for the design are derived. Then, a literature review is conducted to direct the design process, which is followed by the design of the DTEA. The design is then verified by showing that it allows strategic recommendations to be derived for GWH. The evaluation of the DTEA and the recommendations is conducted in the next chapter.

7.1.1 GWH's Goals Related to an Energy Benchmarking DT

The first step in the design science approach is to define the company goals related to the DT uses. The goals of GWH were identified through an interview with the project coordinator, who was identified as the only suitable stakeholder.

In the interview, it was stated that they want to assess and compare the energy performance of different houses, and the different installations within them. They also indicated that the benchmarks should only focus on electricity usage as the relevant energy source. The energy benchmarks should enable them to compare the actual energy consumption to predictions from the design phase and enable them to observe seasonal and day/night differences in the energy consumption. Related to the energy consumption of their installations, they also mentioned that the electricity use of their ventilation system depends on the CO_2 concentration, while that of their heating system depends on the inside and outside temperatures and the user settings for the thermostat. These influences should not be part of the benchmarks. In the end, they intend to use the benchmarks for the development of NZEBs and predicting energy consumption in this context.

To summarize, the following goals were identified:

- The DT can compare the energy performance of different houses and different installations;
- The DT creates benchmarks based on electricity consumption;
- The DT has a temporal distinction to identify seasonal and day/night differences;
- The DT accounts for the influence of factors that should not influence the benchmarks.

7.1.2 Design Requirements of an Energy Benchmarking DT for GWH

The second step of the design science approach is to develop requirements for the artifact based on the stakeholder needs. The needs of GWH were established in the previous section and are now used to formulate the requirements. The following design requirements for an energy benchmarking DT for GWH were formulated:

1. The DT design enables the comparison of the building performance of different houses and to their predicted performance.
   1.1. The artefact addresses how buildings can be compared to one another.
   1.2. The artefact address how buildings are compared to their predicted performance.
2. The DT design can distinguish the energy consumption of different installations from the consumption of the whole house.
3. The DT design enables the performance assessment based on the electricity use.
4. The DT design enables a temporal differentiation of the performance.
   4.1. The artefact addresses a seasonal differentiation in the performance assessment.
   4.2. The artefact addresses a day/night differentiation in the performance assessment.
5. The DT design connects the energy use measurements to measurements of influential factors.
   5.1. The artefact discounts the influence of the indoor CO_2 concentration on the energy performance.
   5.2. The artefact discounts the influence of the outside temperature on the energy performance.
   5.3. The artefact discounts the influence of the inside temperature on the energy performance.
   5.4. The artefact discounts the influence of the thermostat settings on the energy performance.

7.1.3 DT-Based Building Energy Benchmarking Process in Literature

The third step in the design science approach is the design of the artefact. This step is divided into two sections, first, this section will look at the design of the energy benchmarking process for GWH based on scientific literature, then, the next section will use this process to design the DTEA. Based on the requirements of GWH, scientific literature was identified to review these aspects. Figure 28 shows a map of the different goals and relevant papers found concerning them through the Scopus search engine. More papers were identified based on references where more information was needed.

This section delivers a description of steps to design an energy benchmarking process and addresses how each of these steps is applied to the case study.

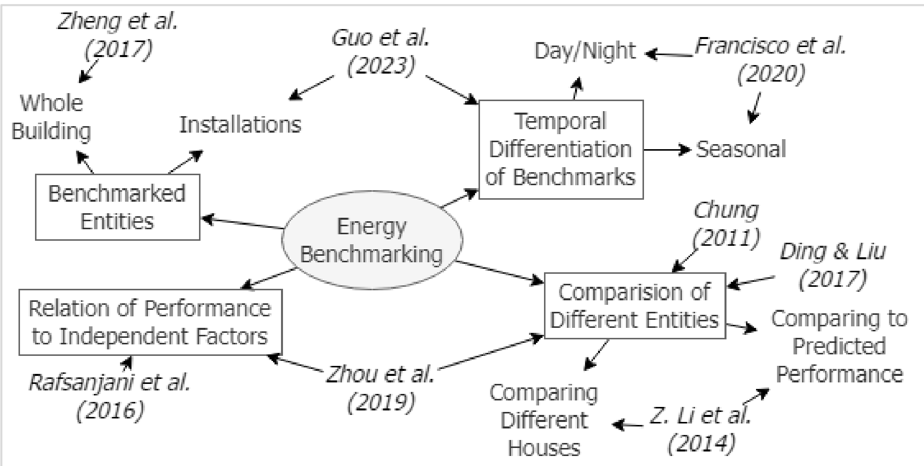


Figure 28: Map of Scientific Literature Corresponding to Different Requirements

EB is a tool used to improve the energy efficiency of buildings and compare the energy use of different entities to identify possibilities for improvement and reveal performance issues (Chung, 2011). The EB process evaluates the performance of different entities, then selects a performance benchmark, and then compares the performance of an entity to the benchmark (Zhou et al., 2019). However, there is no standardized methodology for benchmarking the energy performance of a building, resulting in a limited comparability of benchmarking studies (Ceccolini & Sangi, 2022). Rather, there are many EB procedures that can be applied, varying in their temporal resolution, required input data, and the necessity for modelling experience and calibration of the model (Z. Li et al., 2014). Consequently, the procedure needs a design that considers the project requirements, the available data, and the modelling experience available (Z. Li et al., 2014). To develop this EB process for the DTEA, this research will follow the process developed by Zhou et al. (2019) (Figure 29). This process will be described and applied to GWH in the next sections.

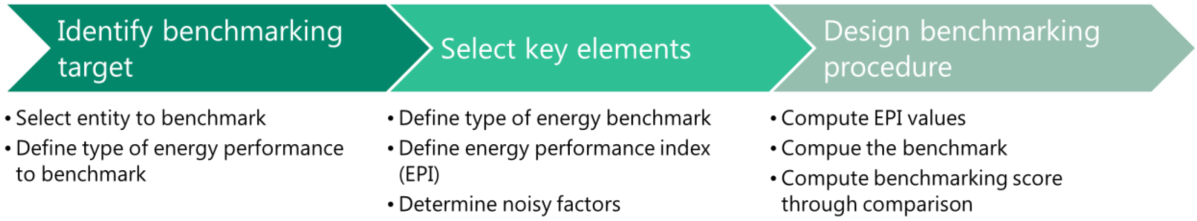


Figure 29: Steps to Develop an Energy Benchmarking Procedure

7.1.3.1 Identify Benchmarking Target

The first step in the process identifies the benchmarking target by defining the entities and type of performance to be compared in the benchmark (Guo et al., 2023; Zhou et al., 2019). The target for a benchmark can be the energy performance of a whole building, as shown by Zheng et al. (2017) and Francisco et al. (2020), but benchmarking can also target the performance of a singular system, as shown by Guo et al. (2023) and Zhou et al. (2019).

Benchmarking Target of GWH

There are several entities that the company intends to benchmark. On the one hand, they are interested in benchmarks of their houses, on the other hand, in benchmarks of specific installations. As the type of performance, GWH specifically mentioned electricity consumption. Thus, two benchmarking targets are defined, (1) total electricity consumption in one house, and (2) the electricity consumption of one installation in one house.

7.1.3.2 Selecting Key Elements

Benchmark Type

For the first key element, the type of benchmark is selected. Zhou et al. (2019) recognized three main types, (1) previous-performance benchmarks which rely on historic data to make a predictive model, (2) intended-performance benchmarks which consider the optimal performance of the system based on a simulation, and (3) peer-performance benchmarks which compare the performance of a system to that of similar systems. The type selected should fit the requirements and purpose of the benchmarks to be developed.

Benchmark Type for GWH: GWH wants to consider a comparison of the performance of different houses/installations to each other, as well as to their predicted performance. Consequently, the DT needs to provide two types of benchmarks, a peer-performance benchmark, and an intended-performance benchmark.

Energy Performance Index (EPI)

The second key element is the energy performance index (EPI), which denotes the comparative value of each measurement, that is used to create the benchmark (Zhou et al., 2019). Its unit, which includes the length of the measuring period, should be defined to suit the intended analysis. The direct measurement of the energy consumption per time period can be used directly, but generally the energy consumption is normalized by other influence factors, the so-called noisy factors (Chung, 2011; Zhou et al., 2019). Often, a simply-normalized EPI is used, which is a normalization on one noisy factor. A common EPI is the energy use intensity, which divides the energy consumption by the floor area of the building, thus accounting for the correlation between floor area and energy consumption (Francisco et al., 2020; Guo et al., 2023; Zhou et al., 2019). More complex EPIs are sometimes preferred to reflect the complexity of energy systems, yet including more factors also requires more data, which increases the cost and reduce the scalability (Zhou et al., 2019). Next to the unit the temporal resolution is important (Zhou et al., 2019). EB often has an annual or daily EPI, but recent studies have shown focuses on operational segments (Zhou et al., 2019), operation periods (Guo et al., 2023), or specific time periods (Francisco et al., 2020). In summary, a finer resolution allows for a more specific interpretation of the results (Francisco et al., 2020). The choice of an EPI and its temporal resolution should be based on the requirements for the intended application and the available data (Zhou et al., 2019).

Energy Performance Index for GWH: The company requires the EPI to reflect the electricity consumption of the house/installation per time period. As GWH has several differing goals for the results, it should be a flexible, commonplace EPI. Consequently, the energy use intensity (EUI) is recommended, as it is commonly used and adaptable (Ding & Liu, 2020). The EUI is expressed as the energy consumption per m^2. The temporal scope of the EPI should vary depending on the assessment. GWH wants to be able to reflect on both seasonal and day/night differences. Thus, two temporal scopes need to be applied for the DTEA. Francisco et al. (2020) showcased benchmarking for different periods through date and time classifications. All measurements falling into a predefined period are used for the benchmark of the period. The seasonal differentiation should specifying the period by date, while the day/night differentiation should be specifying periods by hours.

Noisy Factors

The third key element are the 'noisy factors', which are factors 'whose influences on the energy performance of the benchmarked entities are objective and should not be considered as reasons for the energy performance differences in benchmarking' (Zhou et al., 2019, p. 4). As they make the direct comparison of energy consumption values unreliable, it is recommended to normalize them (Chung, 2011; Guo et al., 2023; Zheng et al., 2017; Zhou et al., 2019). Noisy factors can relate to building characteristics, system characteristics, occupant behavior, as well as climate and environmental factors (Rafsanjani, 2016). Some examples for buildings are structural specifications, weather, installation ownership, and user attributes (Chung, 2011; Zhou et al., 2019). The relevant noisy factors can be derived from physical models for energy consumption (Zhou et al., 2019). Further, a stepwise regression analysis can be conducted to determine the influence of noisy factors on the EPI (Zheng et al., 2017).

Noisy Factors for GWH: In their goals, GWH suggested four noisy factors, the indoor and outdoor temperature, the indoor CO_2 concentration, and the thermostat setting. Other factors might be relevant, but are unknown without a physical model.

7.1.3.3 Benchmarking Procedure

The third step in the process is designing the benchmarking procedure. In this step the EPIs value is calculated, and they compared to a chosen benchmark to calculate the benchmarking scores. To calculate the EPI value, multiple benchmarking models are available. Most studies choose one model based on experience or other criteria (Z. Li et al., 2014; Zhou et al., 2019), however, Ding and Liu (2020) dispute this method and claim several different models should be applied simultaneously to ensure robust results. The choice of the benchmark is dependent on the intended application of the benchmark and the benchmark type (Zhou et al., 2019).

One model is the simple normalization benchmark, which uses a simply-normalized EPI and computes the EPI value by averaging the measured values for each entity (Chung, 2011; Zhou et al., 2019). The entity with the best EPI value is then used as the benchmark, and all EPI are compared to it to obtain the benchmarking score (Zhou et al., 2019). This model is appreciated for its simplicity, yet it ignores the multitude of noisy factors influencing the system and assumes that the noisy factor has a proportional impact on the energy consumption (Zhou et al., 2019). In recent studies more complex models have been preferred, and different studies suggest that simple regression analysis, data envelopment analysis, stochastic frontier analysis, model-based method, and artificial neural networks are commonly used complex models in EB (Chung, 2011; Zhou et al., 2019). They further suggest that the decision for a method should be based on the project requirements, the available input data and the modelling experience available.

Benchmarking Procedure for GWH

GWH aims to use the benchmarks to identify design improvements, as well as compare and predict the energy consumption. Using the overview of EB methods from Z. Li et al. (2014), there are four benchmarking models identified that fit the intended applications and the temporal resolution of the EPI: artificial neural network, RC network, idealized model based, and detailed simulation. The decision on a method will depend on the available data, and the effort to be invested in building and maintaining the model.

7.1.3.4 Conclusion

This section designed different aspects of a benchmarking procedure for GWH. The benchmarking target was set as the electricity consumption of each house and each installation in the house. Further, the DT should provide peer-performance and intended-performance benchmarks, and the energy performance should be measured as the EUI of the entities in energy consumption per m^2. Additionally, four noisy factors need to be included, the indoor and outdoor temperature, the CO_2 concentration, and the thermostat settings. Lastly, four benchmarking models were identified to be implementable for the benchmarking procedure.

7.1.4 DTEA for an Energy Benchmarking DT for GWH

The second part of the design phase will design the DTEA for EB based on the design requirements and the decisions made in the previous section. The DTEA is based on the questions in Table 4, which were reflected on to design it. The resulting DTEA for building energy benchmarking is presented in Figure 30. A more detailed overview of the elements in each layer is given in Appendix D: Descriptive DTEA Energy Benchmarking.

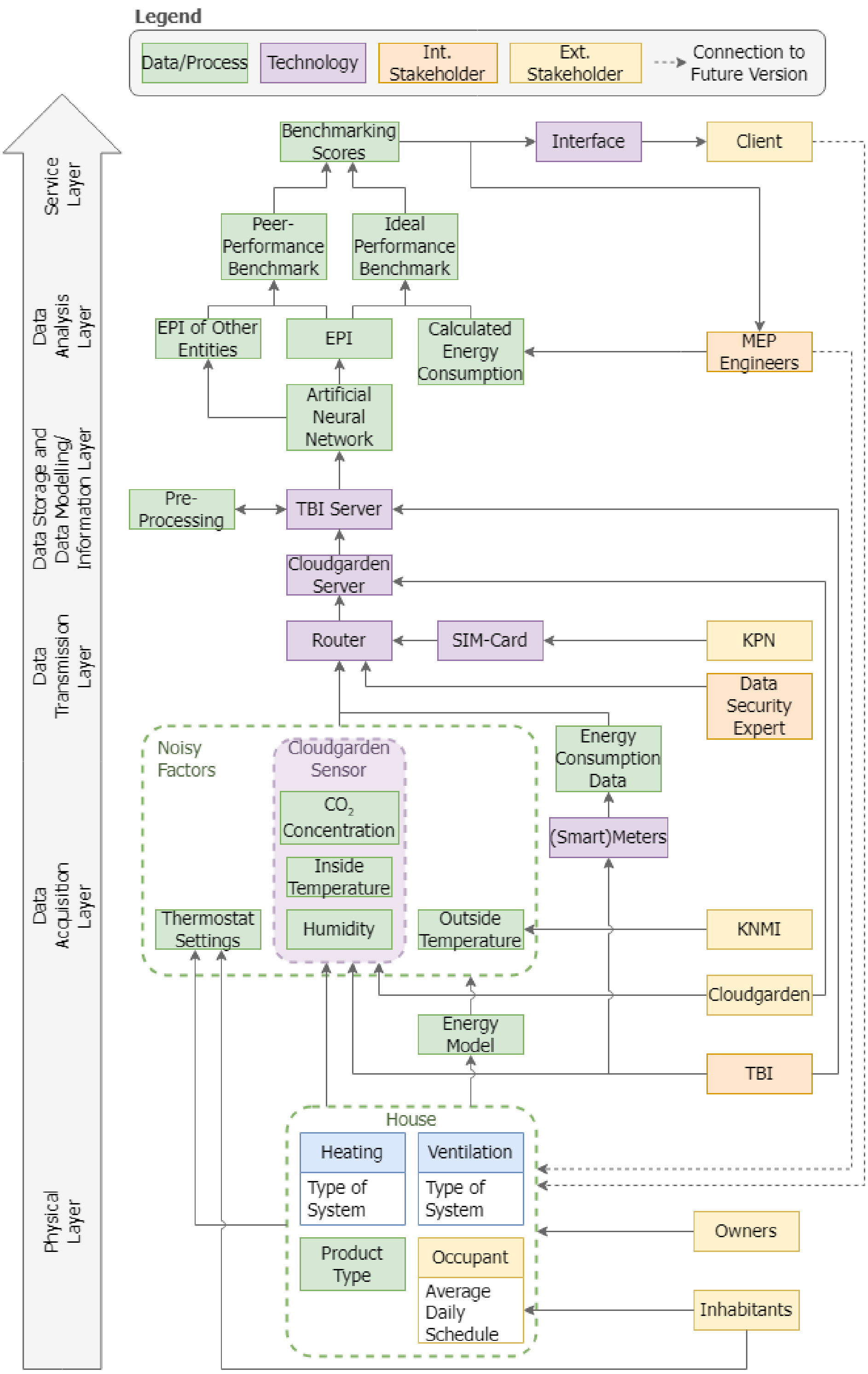


Figure 30: Visualization of Building Energy Benchmarking DTEA

The next sections will explain the decision-making and process behind the DTEA. The process was intended to follow Figure 11, and develop the DTEA based on scientific literature, and then compare it to the current situation. However, during the design process it was found that a more iterative approach was needed to clarify further decisions. Thus, the comparison is expanded to also evaluate any open decisions and revise the framework accordingly. Consequently, there is a preliminary design, and then a revision of the DTEA based on the evaluation. For this DT, two evaluations were conducted, one with the project coordinator, and one with a data collection expert from TBI.

7.1.4.1 Physical Layer

Preliminary Design

Based on the requirements and the literature review, the physical assets pertaining to the DT system are the house, the installations, and the occupants. Further, the sensors to be connected to this layer need to be included. Next to the assets themselves, it was found that their characteristics might be relevant, such as the age or frequency of use of the installations, the floor area of the house, or the behavior and decisions of the occupants. Considered are characteristics of the assets that are relevant for the assessment. These might provide important static data for the further processes. To order the elements in a hierarchical structure, it is suggested to use the house as the system, with the assets inside the house being its elements, and then presenting the characteristics in the third layer. This potential hierarchical structure is visualized in Figure 31(left).

Next, the stakeholders need to be identified. When collecting data in residential houses, the privacy and ethics of the data collection need to be considered to protect the occupants (Du et al., 2020; Sharpe, 2019). These need to be considered and the cooperation of the inhabitants assured. Further, due to them not owning the houses, the owners need to allow them access to the houses.

Evaluation & Final Design

The interview assessed that the required data was available, and that the connection to the stakeholders was already contractually secured through the purchase and rental contracts. This process is done in accordance with the General Data Protection Regulations (GDPR, NL: Algemene Verordening Gegevensbescherming), which mandates to create a transparent process and inform the participants (RVO, 2021a). Further, it was determined that some of the characteristics were irrelevant for the comparison intended by GWH, thus the age and frequency of use, as well as the floor area were excluded. Further, they decided to only compare houses of the same product type, only consider the heating and ventilation as installations, and want to compare only installations of a different type. Additionally, it was determined that there are smart meters for electricity, as well as sensors connected each installation. Lastly, GWH suggested to take occupant behavior into account, and that they were developing a system to record this data, for example trying to estimate when inhabitants are home.

Based on the interview, new characteristics were included, such as the type of the house and the type of the installations, and the sensors connected to each installation to be able to connect their data to the right installations. Due to the collection method of the occupant behavior, it is reclassified as dynamic data, and will thus not be included in the physical layer anymore. To reflect the changes, the hierarchical structure was updated as displayed in Figure 31 (right). The installations were defined as the heating and the ventilation systems, and their characteristics were limited to the type of system they are and information about the sensor they connect to. In the building characteristics section, the floor area was removed, and replaced by the identification of the building type. The occupant behavior was removed entirely, while the sensors and communication were redefined to reflect the connection to the sensors in the building.

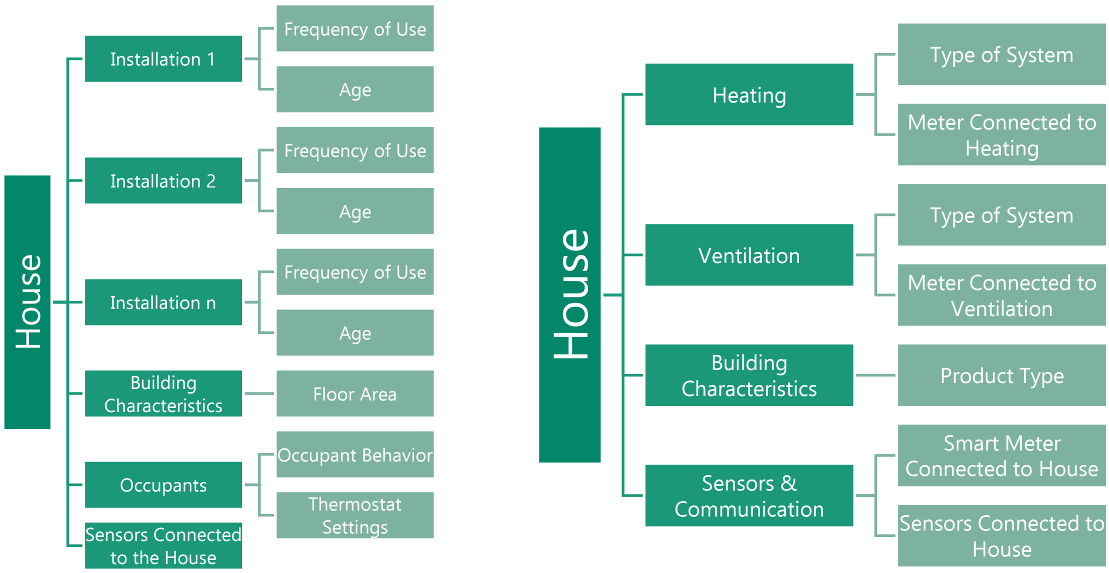


Figure 31: Preliminary (Left) and Final (Right) Potential Hierarchical Structure of the Physical Layer

7.1.4.2 Data Acquisition Layer

Preliminary Design

The data to be acquired in this layer is all dynamic data needed for the DT design. Thus, the data to be collected is electricity data, both from the house as a whole, but also from the separate installations. Also, to include the identified noisy factors, data regarding the inside and outside temperature, the CO_2 concentration of indoor air, and the thermostat settings needs to be collected. The measurements need to have at least an hourly frequency to fit the temporal scope of the benchmarks, and the measurements needs to be connected to the date and time they were taken at. For the technology, sensing devices able to collect the necessary data need to be installed. A relevant stakeholder was identified as the producer of the sensors to be installed, further, the data ownership will be relevant.

Evaluation & Final Design

During the interview, it was found that there was no physical model to verify the identified data needs, thus they are all based on estimates from GWH. They stated that all identified data needs were available through sensors already installed in their houses, which conduct sub-hourly measurements of all variables. Further, they were able to request the thermostat settings from the thermostat. They also collect data on the outside temperature from the database of the Dutch Meteorology Institute (KNMI). GWH also mentioned that some of the data collection itself was not conducted by them directly, but through their mother company TBI. The sensors were created and equipped by Cloudgarden, but then bought by GWH. They were also installed and maintained by GWH, however, little need for maintenance in the predicted measurement period is expected. The indoor humidity was suggested as another noisy factor to consider for the analysis, the data for which was also already available. The data collected was owned by TBI, and cannot be accessed by any third party for data security reasons. While the thermostat settings were first seen as static data, they were reclassified as dynamic data streams as they are time-sensitive. Additional newly-identified noisy factors are the humidity, and the occupant behavior.

7.1.4.3 Data Transmission Layer

Preliminary Design

The data transmission layer needs to transmit the data collected from any sensors installed in the houses to a storage location to be assessed by GWH. The houses of GWH are in different locations throughout the Netherlands, and the data collection frequency is sub-hourly. Thus, the transmission system needs to be scalable to wide distances, and either have a frequent transmission rate or be able to temporarily store the data. Further, the data privacy and security need to be addressed. This relates for example to potential government regulations about the matter.

Evaluation & Final Design

During the interview, the existence of a transmission system for the sensors already installed was confirmed. It was designed and programmed by Cloudgarden under the direction of TBI. The system used a router which collected the data from all sensors in the house. A SIM-card from KPN provided an internet connection for the router, allowing it to send the data to a Cloudgarden server through the internet. This data transfer happened at least every 60 mins. The data on the Cloudgarden server was accessed by TBI through an API, which transfers the data to their own server. Further, the interview confirmed that there were data security regulations that must be followed for the transmission of the data. GWH did not have necessary knowledge about data security, thus TBI is currently managing this aspect. However, GWH was interested in getting more knowledgeable about the topic.

Based on this evaluation, three new stakeholders were identified in Cloudgarden, TBI, and KPN. Further, new technological elements for the transmission were identified in the router, the SIM-cards, and any physical connections needed to connect the sensors to the router. The data security is integrated in the current transmission process through an external party and should be kept updated with new regulations. However, there could be a better communication between GWH and the external parties about the data security needs and measures.

7.1.4.4 Data Storage and Digital Model/Information Layer

Preliminary Design

In this layer, the data collected needs to be preprocessed to prepare it for data analysis, and stored for the data analysis. The storage needs to be able to store the data of all parameters that are collected through the sensors. Further, this layer needs to integrate the homogenous data through the preprocessing to prepare it for the analysis. The static data considered are the assets and their characteristics in the physical layer, while the dynamic data is all data collected in the data acquisition layer through sensing technologies. In this case, the electricity data and noisy factors need to be connected to their physical assets (if available), their time and date, and each other. To conduct the preparation and integration of the data, different technologies might be needed depending on the process.

Evaluation & Final Design

The interview found, that the data is currently stored on a TBI server, that can be accessed by an API to collect the data for processing and analysis. The storage is estimated to have the capacity to meet the future demand, and the data from new houses can be easily connected to the existing system. However, no processing is currently conducted by GWH, nor do they have the skill available.

7.1.4.5 Data Analysis Layer

Preliminary Design

The data analysis layer needs to conduct the benchmarking procedure, thus it needs to calculate the EPI values, select a benchmark, and calculate the benchmarking scores. It was found that there are four benchmarking models that could support an EB process for GWH. A decision has to be made based on the available input data, the modelling and calibration effort needed, and the amount of training data necessary. Then the EPI value is calculated in the energy consumption per m^2. For the selection of benchmark values, the benchmark type needs to be considered. It was found that the DT needs to conduct two benchmarking types to satisfy GWHs goals. On the one hand, they need a peer-performance benchmark, where the benchmark is selected as the best performing house design/ installation. On the other hand, they need an intended-performance benchmark, where the benchmark is the prediction made for the design or installation. This also requires having predicted performance data available. The benchmarking scores are created through dividing the EPI value by the benchmark.

For the computer system structure, a cloud computing approach is recommended, as the amount of data is manageable, and it is easier to maintain. The necessary technology depends on any software or programs able to conduct the data analysis and the benchmark model algorithm. As stakeholders, data analysts or people with the skills to operate the benchmark models are required.

Evaluation & Final Design

GWH was hesitant about the EPI suggested, instead they suggested excluding the floor area, as they would only compare houses of the same product type, and thus with the same floor area. Further, they suggested that they were interested in a benchmarking model with low effort to create and maintain, as they did not have any specialists available. They further assessed that they did not have the data analysts or technology available that might be required.

Based on these results, the EPI unit was adapted to reflect the priorities of the companies. Through the comparison between buildings of the same floor area only, the floor area can be eliminated as the factor for normalization. As a result, it is recommended to use the direct energy consumption measurement as the unit. Including the aggregation periods decided on by the company, the EPI would then be the total (monthly/hourly) energy consumption in (measured energy unit) per (house/installation(s)).

Based on the preferences of GWH for a benchmark model, it is recommended to use an artificial neural network, as it has the lowest requirements for modelling experience and calibration (Z. Li et al., 2014). Further, it is a white box method, which is preferred over a black box method if detailed building data is available, and supports intended-performance benchmark better (Z. Li et al., 2014; Zhou et al., 2019).

7.1.4.6 Service Layer

Preliminary Design

In this layer, the benchmarking scores need to be interpreted and utilized for decision making. This will contain an interpretation process to draw conclusions, a presentation process, where the results are presented to the users, and a feedback process, where the decisions are made and directed back at the design. Thus, the users and their needs need to be determined, as well as the decisions to be made. Further, visualizations of the data for the users need to be designed. There were little requirements for the design of this part in the requirements, thus they will be further assessed in the evaluation.

Evaluation & Revision

GWH identified two internal users, the MEP engineers and the installation company, and an external user in the clients. The MEP engineers were to interpret the data, and conduct the decision-making for improvements. However, the information they would need for this process was not known. The users of the DT would be mainly internal, such as the MEP engineers and installations company. Further, the results would be presented for future clients, and new clientele regarding advisory work. For their own calculations they want to be able to see whether the consumption matches their prediction, and then leave it up to the MEP engineers to make decisions based on the results. They further have few preferences regarding the visualization of the results, yet iterate that there should be an automatic, fixed interface that requires little additional work to be operated.

The users were defined as both professionals in the MEP industry, as well as clients, thus, at least two interfaces are needed. Consequently, the information needs of both parties need to be defined to determine what requirements each interface has. The feedback loop is designed as a passive feedback loop, with the MEP engineers making the decisions and implementing the feedback.

7.1.5 Strategic Advice

The fourth phase of the design science approach demonstrates the artefact, in this case the demonstration is conducted by developing strategic recommendations from the DT. They are derived based on the process in Figure 11. The results are summarized in Figure 33 and Figure 34. Each layer is colored to indicate the gap of the layer and give a quick overview on what layers need the most work to be functional. As shown in Figure 32, the layer can be dark green indicates that the layer is mostly/fully complete (e.g. the data process, technology, and stakeholder structures exist and function as needed for the DT), while orange indicates that the layer does not yet exist or needs to be significantly restructured.

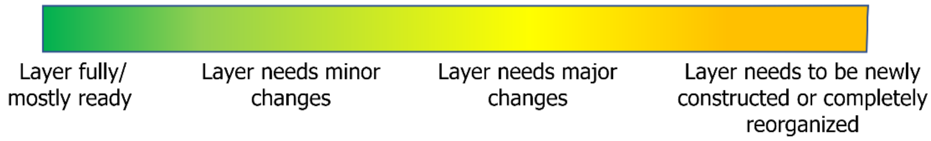


Figure 32: Color Scheme for Strategic DT Development Recommendations

The overview shows that the data collection and transmission layers are already prepared and need little work to enable a DT. In contrast, the data analysis layer and the service layer need to be newly developed and should be the focus of future developments. Especially, the intended application of the results is still very vague. Thus, a plan on what results are important and how they will be used, needs to be made before diving further into the technical development. Another important decision is whether to develop the data processing and data analysis internally, which would require GWH to acquire new capacities and skills or hire an external party to develop it for them.

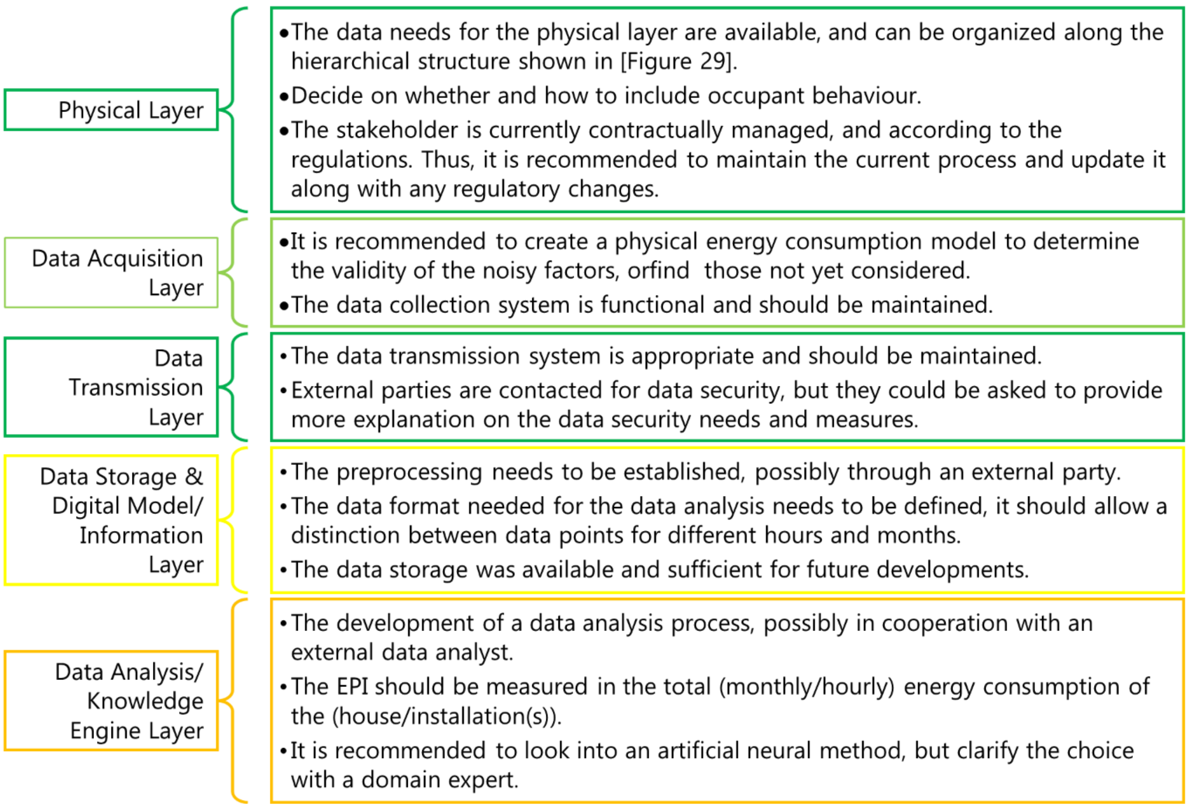


Figure 33: Strategic Recommendations for the Development of an Energy Benchmarking DT for GWH (1)

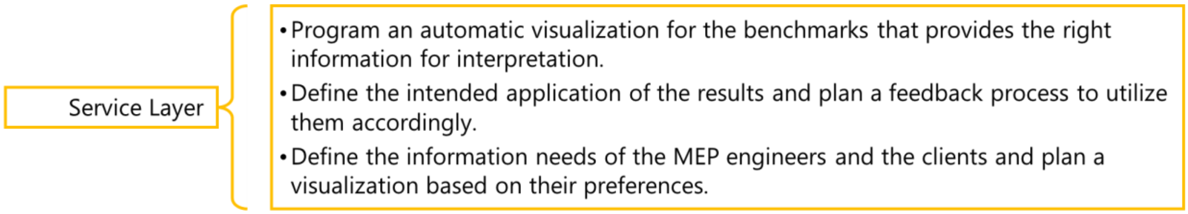


Figure 34: Strategic Recommendations for the Development of an Energy Benchmarking DT for GWH (2)

7.2 BIM-Based Life Cycle Assessment

The second part of the case study develops recommendations for GWH regarding the development of a DT for a BIM-based LCA. Further, it derives strategic recommendations from it using the process detailed in Figure 11. The process of this section follows the design science structure detailed in Figure 6. First, the next section identifies the goals of the stakeholder for the DT, from which the requirements for the design are derived. Then, a literature review is conducted to direct the design process, which is followed by the design of the DTEA. The design is then verified by showing that it allows strategic recommendations to be derived for GWH. The evaluation of the DTEA and the recommendations is conducted in the next chapter.

7.2.1 GWH's Goals for a BIM-Based LCA DT

The first step of the design science approach requires the identification of GWHs goals for the DT design. In the interview, they stated that an LCA is crucial to their proceedings, as they require them to obtain permits for their projects from the municipalities or to get funding for subsidized projects. They also expect government initiatives, such as the 'Paris Proof Commitment' reporting or CO_2 taxing to come into effect and want to prepare for their implementation. To meet these conditions, they require the LCA to follow the Dutch regulations for the calculation of the environmental performance of buildings (EPB, NL: MilieuPrestatie Gebouwen). To add an LCA to their processes, they need the LCA to be as automated as possible, due to limited additional capacities. Thus, they want to calculate the impacts directly from their BIM models and conduct the LCA through a software plug-in connected to the BIM software. The DT should also automatically assign environmental product declarations (EPDs) to the materials in the BIM model to lower the manual effort. The data format used in the BIM model should cooperate with the NLsfb code, the Dutch semantic standard used for BIM.

Further, the calculation needs to be connected to the Nationale Milieu Database (NMD), which offers them EPDs for the assessment of Dutch construction projects in accordance with national regulations. Next, they expressed a desire to have a high specificity in their results to be able to make more sustainable material choices on the product level based on the assessment. Lastly, they found that the EPDs in the NMD change quite often, which might change the results of their calculations significantly. Thus, they would like to be informed when changes are made to the EPDs within their products, and what the change will mean for their assessments. On the other hand, they also want to be able to 'freeze' the LCAs of finished projects, so that their results do not change based on updates to the underlying EPDs. Additionally, they have specific goals for the results of the LCA. They would like to be able to see the changes in the calculation as soon as possible after the changes are made in the model. Ideally, their results would be visualized in the BIM models, and they would be able to visualize the differences between models. For their clients they want a dashboard for the results and provide material comparisons to show the impact of their decisions.

To summarize, their goals are:

- LCA procedure needs to adhere to governmental regulations for the process;

- A highly automated process, based on a BIM model formatted in the NLsfb format and a plug-
- Connection to the NMD for product EPDs;
- High detail in their results to enable material level decisions;
- Being informed about updates to EPDs in their designs;
- Freeze the LCA results of their designs when the design stage is over;
- Present the DT uses in form of a dashboard and visualize them in the BIM model.

7.2.2 Design Requirements of a BIM-Based LCA DT for GWH

The second step in the design science approach is formulating requirements based on the goals identified in the last chapter. The following design requirements were formulated for a BIM-based LCA DT for GWH:

1. The DT design provides a highly automated process.
   1.1. The assessment is directly derived from the BIM model.
   1.2. The assessment is conducted through a software plug-in for BIM.
   1.3. The artefact automatically connects material EPDs to the material quantities from the BIM model.
   1.4. The artefact structures the BIM model data in the NLsfb format.
2. The DT design conforms with national regulations regarding LCAs.
3. The DT design uses EPDs from the NMD as input for environmental data.
4. The planned DT will allow for material level design decisions to be made.
   4.1. The artefact enables the user to compare the environmental impacts of different material choices for their design.
   4.2. The artefact plans for a high specificity of the LCA results.
5. The DT informs the user of updates to the EPDs used in their designs.
6. The DT design provides visualizations for different users.
   6.1. The artefact includes a dashboard to visualize the data.
   6.2. The dashboard can be used to compare different design choices.
   6.3. The artefact can visualize the DT results within the BIM model.
7. The results on a project level will not change after the completion of the project.

7.2.3 Governmental Regulations in the Netherlands

This section reviews international, European, and Dutch legislation to determine the requirements for an LCA process to comply with the Dutch standardized methods. The LCA process is standardized in international and national norms, which will be used as a basis for the BIM-based LCA process. The term and process of LCAs have been internationally normed through ISO 14040 (ISO, 2006b) and ISO 14044 (ISO, 2006c), wherein an LCA is defined as a 'compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its lifecycle' (ISO, 2006b, p. 2). In a building context, an LCA should follow the national directive of NEN-EN 15978:2011 (NEN, 2011) and NEN-EN-15804:2012+A2:2019 (NEN, 2021), which are based on the international norms, and dictate the processes and steps involved in conducting an LCA for a building and building material EPDs.

7.2.3.1 Streamlining Dutch Building Assessments

The government is interested in conducting LCAs for building construction in the Netherlands. Due to the agreements the Netherlands made to reach net-zero CO_2 emissions over the next few decades, efforts are made to reduce the impact of the construction industry as a main contributor to the national carbon emissions (De Circulaire Bouweconomie, n.d.). The Environmental Performance of Buildings (EPB) is an important, LCA-based tool for measuring the sustainability of construction projects in the Netherlands and is used to set sustainability goals for the Dutch construction industry in the coming years (De Circulaire Bouweconomie, n.d.; RVO, 2021b). Its calculation process is based on European norms NEN-EN 15978 (NEN, 2011), regarding the assessment of the environmental impact of buildings, and NEN-EN 15804 (NEN, 2021), which documents the core rules for EPDs of construction products (NMD, n.d.-d). While following the general structure of the European norms, the NMD specifies aspects that are left open in the European norms for the Dutch context (NMD, n.d.-d). The NMD documents this Dutch calculation process in their 'Environmental Performance Assessment Method for Construction Works' (EPAM-CW) (NMD, 2022). The report specifies the Dutch calculation process yet requires the simultaneous use of NEN-EN 15804 (NEN, 2021), ISO 14044 (ISO, 2006c), and ISO 14025 (ISO, 2006a) to fully understand. The goal of streamlining this process for the Dutch construction industry is ensure the uniformity and comparability of the environmental performance (NMD, 2020, 2022).

7.2.3.2 Environmental Product Declarations (EPDs)

An EPD is a representation of the environmental performance of a product, which summarizes the results of a product-level LCA report, without revealing any sensitive product information (Liebsch, 2019). The EPDs of different building materials for a range of suppliers in the Netherlands are collected and verified by the National Environmental Database (NMD, NL: Nationale Milieu Database) (NMD, n.d.-a). An EPD needs to contain the general product information and the environmental profile of the material (NMD, 2022). The environmental profile presents the results of a product-level LCA as a list of 19 indicators defined in the NEN-EN 15804 (NEN, 2021), which are given per unit of building material. Additionally, EPDs have to follow the procedure of the NMD and be verified to be valid for EPB calculations. To obtain such an EPD for their materials, a company needs conduct a professional LCA for their product, and then verify it according to the NMD verification protocol. An EPD in the NMD is valid for 5 years, after which it needs to be renewed (NMD, n.d.-c).

Within the NMD, EPDs can be classified into three categories described in Figure 35 (NMD, 2022). The first category includes EPDs that refer to one specific product produced by one specific supplier. The second category includes EPDs representing the average environmental data for a product based on the Dutch market or a specific group of manufacturers. The last category represents a generic environmental profile based on generic processes created through NMD. Product cards in categories 1 and 2 are always preferred to those of category three, especially, because EPDs in category 3 are required to have a worse environmental performance than any comparable product with a verified product card (NMD, 2022). As unverified product cards often underestimate the actual environmental impact, they also have a 'surcharge factor' of 30% that is used to account for uncertainties (NMD, 2022).

Figure 35: EPD Classification in the NMD

7.2.3.3 Building Level Assessment

On the building level, the EPAM-CW needs to be followed based on the calculation rules for the EPB given by the NMD (2021a, 2021b). This calculation is based on the environmental impacts given by the product EPDs. In the process, the different environmental impacts of a product are combined in a single score, the environmental cost indicator (ECI) (NL: Milieukostenidicator, MKI)(Hillege, 2019; RVO, 2021b). This enables the comparison of different impacts that are otherwise not directly comparable. The ECI is assigns a monetary value to different impacts and is expressed in Euro (€) (Hillege, 2019). To assess the ECI of a building, the ECI of all materials used in all life cycle phases of the building are summated (NMD, 2021a). Finally, the ECI is transformed into the EPB by dividing the building ECI by its gross floor area (GFA) (NL: Bruto Vloeroppervlakte, BVO) in m^2, and its expected service life in years (Hillege, 2019; RVO, 2021b). Thus, the MPG is expressed in €/m^2/yr (RVO, 2021b).

7.2.3.4 Calculation Tools

To comply with the regulations of the NMD, a verified software tool is required for conducting the LCA. These are private LCA software that are licensed to conduct an LCA in accordance with the Dutch calculation standard (NMD, 2021b). Only these verified programs can access the product card database and use the information stored within. The NMD currently has four programs verified for structure-related EPB calculations. These include GPR Materiaal by W/E Adviseurs, MPG Toetshulp by Bimpact B.V., One Click LCA, and the MRPI-MPG Tool by Stichting MRPI (NMD, n.d.-b).

7.2.3.5 Conclusion

This section has reviewed international, European, and Dutch legislation to determine the requirements for an LCA process to comply with the Dutch standardized methods. It was found that:

- The results of the LCA are given in €/m^2/yr, thus requiring the ECI, the GFA, and the service life;
- The process needs to follow the EPAM-CW and use the EPDs from the NMD;
- The EPDs should be of the most specific category possible to reach more specific results;
- The LCA needs to be conducted through a verified LCA software tool to access the NMD.

7.2.4 BIM-based Building Life Cycle Assessment Structure

The process of an LCA is regulated in the international standards ISO14040 and ISO14044, however, the process needs to be connected to a BIM model to achieve the desired level of automation and to the DTEA for the design. This section aims to connect these three aspects, and identify the elements in each layer of the DTEA.

The ISO describes the concept of an LCA as a method that ‘addresses the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal’ (ISO, 2006b, p. 1). An LCA can be applied by helping to (1) identify improvements to the environmental performance, (2) inform decision-makers, (3) select environmental performance indicators and measurement techniques, and (4) market your product (ISO, 2006b). The assessment of the lifecycle impacts of a product using an LCA should follow the four steps outlined in Figure 36 (ISO, 2006b). The first step is the goal and scope definition, followed by the life cycle inventory analysis (LCI), and the life cycle impact assessment (LCIA). The final stage of the LCA is the interpretation, in which also insights from all phases of the assessment need to be considered. The interpreted results can then be used for the intended application.

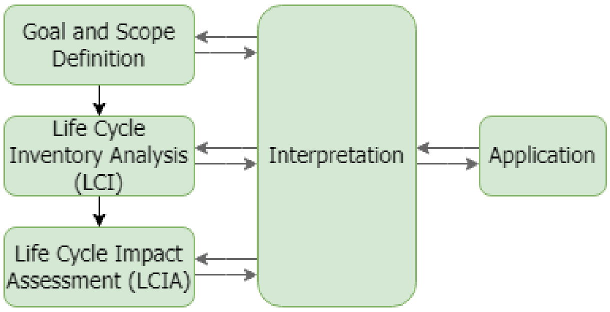


Figure 36: Steps of a Life Cycle Analysis (ISO 14040)

Based on practical insights, Wastiels and Decuypere (2019) determined six basic steps that are necessary to conduct a BIM-based LCA assessment as described in Figure 19 (see Section 6.2.4). The steps of the ISO method and the BIM-based process should be linked to one another and to their corresponding layers in the DTEA. This helps to structure the information in the DTEA and ensures that all steps of both processes are implemented without any recurrence.

7.2.4.1 Goal and Scope Definition

The first step in an LCA is defining the goal and scope, which means defining what is to be assessed and the framework for this assessment (NEN, 2011). This includes a description of the entity to be assessed and its functional unit, the system boundaries related to the life cycle of the entity, the methodology used for the assessment, and the impact categories considered (Quist, 2019).

As this aspect of the LCA process precedes the assessment process from Wastiels and Decuypere (2019) and lays the groundwork for the assessment. Thus, the goal and scope definition of a DT for LCA assessments should precede and guide the design of the DT in a preparatory step.

7.2.4.2 Life Cycle Inventory Analysis (LCI)

The second step is the life cycle inventory analysis phase, which is a 'quantification of inputs and outputs for a product throughout its life cycle' (NEN, 2021, p. 10). This step should quantify all relevant flows for the considered processes and scale them to the scope of the project. This means allocating all resources, energy, waste, and emissions that flow in or out of the system boundaries defined in the goal and scope (Quist, 2019). The Dutch legislation determines that the resources to be defined to analyze the building emissions are the materials used to build the house, and the flows related to their production, transport, use, and demolition (NMD, 2022). It further specifies, that the flows for the materials should be defined through product EPDs stored and verified by the NMD.

Linking the inventory analysis to the process defined by Wastiels and Decuypere (2019), there are four steps to be conducted to connect the LCI to BIM and identify all material flows. First, it needs to create a detailed BIM model, extract the model quantities, establish the LCA profiles of different materials, and link the profiles to the quantities. The technological requirements to conduct these steps are a BIM software to build the model and gather its material quantities, and an LCA software to establish the LCA profiles. Further, the software should have some interoperability to link the profiles to the quantities. Regarding the DTEA, the creation of the BIM model corresponds to the modelling aspect in the data storage & digital model/information layer, where a BIM model has to be created in the necessary level of detail. The material quantities can be provided through a bill of quantities gathered directly from a detailed BIM model (Hollberg et al., 2020; Kaewunruen et al., 2020; Wastiels & Decuypere, 2019). This gathering connects to the data storage & digital model/ information layer, or the data analysis/knowledge engine layer, depending on how and when the quantities are extracted. If the bill of quantities is extracted, stored, and then connected to the LCA profiles, the extraction process would correspond to the preprocessing of the data in the data storage & digital model/information layer. Using an LCA software, that can directly extract the quantities from the BIM model requires no preprocessing. Thus, the extraction of the quantities is connected to the data analysis/knowledge engine layer, where the data accessed through the analysis software. The establishment of LCA profiles relates to the data acquisition layer, as they are a dynamic data set to be collected for each project. Lastly, linking the LCA profiles to the materials corresponds to the data storage & digital model/ information layer as part of the preprocessing of the data.

7.2.4.3 Life Cycle Impact Assessment (LCIA)

The third step is the life cycle impact assessment, which aims to evaluate the potential environmental impacts using the data collected in the LCI. The resulting assessment depends on the indicators and impact categories defined in the goal and scope. This step includes connecting the flows from the LCI to the different impact categories, equate them to a common unit, and summarize them to represent the total impact of the entity (Quist, 2019). In the BIM-based LCA process, this relates to the calculation of the impact using the LCA profiles. Consequently, the task is calculating the total impacts of every material based on its quantity and summarizing them for all materials in the house. Most of this process is conducted within the LCA software. This process corresponds to the data analysis/knowledge engine layer of the DT, as it aims to assess and organize the collected data.

7.2.4.4 Interpretation

The last step in the LCA process is the interpretation, this should reflect on the results of the LCI and LCIA, identify the limitations, and give conclusions and recommendations based on the results (ISO, 2006b). This might explicate on the total impact of the product, the contribution of different elements, and the elements with the highest potential for reducing the impact (Quist, 2019). In the process defined by Wastiels and Decuypere (2019), this step corresponds to the visualization and analysis of results. This corresponds best to the service layer of the DTEA.

7.2.4.5 Conclusion

This section has reviewed the standardized LCA process defined in ISO standards, and established a connection between the standardized method, the BIM-based process, and their linkage to the DTEA layers. Table 17 summarizes these connections, which will be used to design the DTEA.

Table 17: Connection Between the Standardized LCA Process, the BIM-Based LCA Process, and the DTEA Layers

Standardized LCA Process	BIM-Based LCA Process	DT Layer
Life Cycle Inventory Analysis (LCI)	Detailed BIM modelling	Data Storage & Digital Model/ Information Layer
	Extraction of model quantities	Data Analysis/Knowledge Engine Layer *or* Data Storage & Digital Model/ Information Layer
	Establishing LCA profiles of different materials	Data Acquisition
	Link the LCA profiles to the different quantities	Data Storage & Digital Model/ Information Layer
Life Cycle Impact Assessment (LCIA)	Calculate the impact	Data Analysis/Knowledge Engine Layer
Interpretation	Visualize and analyze the results	Service Layer

7.2.5 Goal and Scope for GWHs LCA Process

The goal of the LCA is assessing the environmental performance of prefabricated, wooden, residential houses in the design phase to make design decisions and ensure complacency with current and future regulations. The functional unit is one residential house including all relevant components as defined in NEN-EN 15978 (NEN, 2011), and the results should be expressed as the EPB in €/m2/yr. The system boundaries will follow the EPB method outlined by the EPB guidelines (NMD, 2022), and include the life cycles stages A, B 1-5, C and D. The impact categories and characterization model are also defined in the EPB guidelines (NMD, 2022), and include 19 impact categories. More detailed aspects of the goal and scope are defined in NEN-EN-15804 (NEN, 2021) and the EPB guidelines (NMD, 2022).

7.2.6 DT Element Architecture Design for a BIM-Based LCA at GWH

The second part of the design phase will design the DTEA for a BIM-based LCA based on the design requirements and the information gathered in the previous sections. The DTEA is based on the questions in Table 4, which are reflected on to design it. The resulting DTEA for a BIM-based LCA is presented in Figure 37. A more detailed overview of the elements in each layer is given in Appendix E: Descriptive DTEA BIM-Based LCA.

The next sections will explain the decision-making and process behind each layer of the DTEA. The process was intended to follow Figure 11, and develop the DTEA based on the governmental regulations and practical insights, to then compare it to the current situation. However, during the design process it was found that a more iterative approach was needed to clarify further decisions with GWH. Thus, the evaluations were conducted to discuss any open decisions and revise the framework accordingly. Consequently, there is a preliminary design, and then a revision of the DTEA based on the evaluation. For this DT, evaluations of the current situation were conducted with the project coordinator of GWH and a building physics expert of TBI. Additionally, information on the software of One Click LCA was gathered through a meeting with a One Click LCA employee.

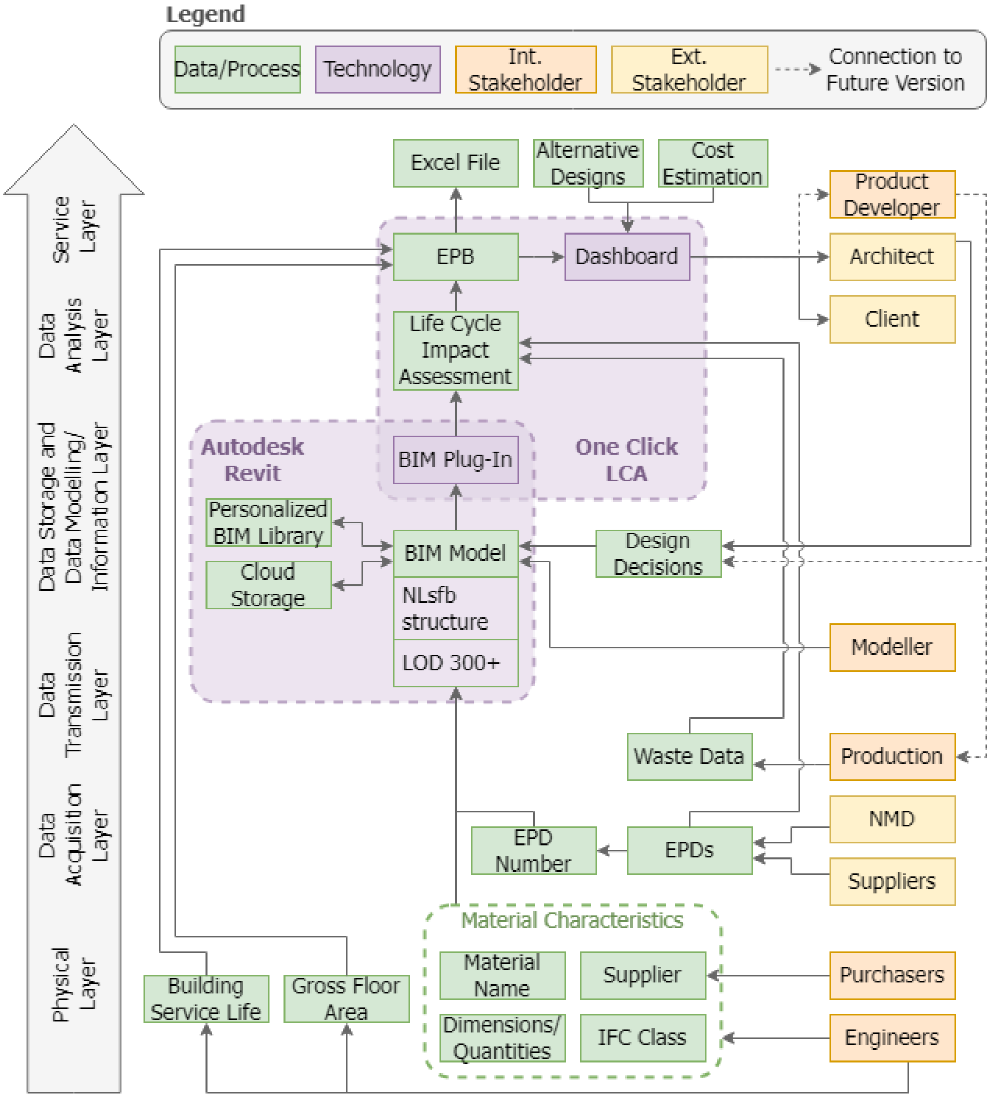


Figure 37: Visualization of a BIM-based LC A DTEA

7.2.6.1 Physical Layer

Preliminary Design

For the physical layer, the house, its structure, and all constructed objects inside are of relevance. As this DT is used in the design phase, and therefore before the building is built in the physical world, the physical layer will be comprised of the designed objects, as they are planned to be built in the future. This layer also collects the characteristics of these physical objects in the detail needed for the BIM model. One Click LCA provides a guideline for the level of detail necessary for the BIM model to facilitate different applications with the LCA results (One Click LCA, 2022c). For making specific design development choices, and using the assessment for specifications or bidding, they recommend using a BIM model of LOD 300+. Further, they provide an overview of the data requirements for the BIM model based on the LOD (One Click LCA, 2022c).

A LOD 300+ model should be (nearly) complete and include all items that will be constructed. Further, a specific set of characteristics has to be collected for each item. First, the dimensions and/or quantity of each item should be given as accurately as possible, but definitely within a ±3.5 % error margin. This includes considering any hollow spaces. Next, the quantities of the items should be given in a recognized unit. In the NMD, quantities are most commonly given in m2, but kg or m3 can also be used for specific materials (One Click LCA, 2023b). Additionally, for every item a supplier and a non-generic material name should be available (One Click LCA, 2022c). It is also recommended to define the IFC class for every item (One Click LCA, 2022c). IFC is an 'open international standard for Building Information Model (BIM) data that are exchanged and shared among software applications used by the various participants in the construction or facility management industry sector' (ISO, 2018). This standard provides a hierarchy-based breakdown of structural elements and other objects related to the construction industry. Consequently, it would be recommended to utilize this standardized, hierarchical structure to organize the elements and their characteristics in the physical layer. Next to the data on the individual items, the EPB calculations require further characteristics of the house, such as the GFA and the building service life. The GFA is defined according to NEN 2580 (NEN, 2007) and given in m^2. The building service life generally depends on the type of building, but can be adapted for specific circumstances (NMD, 2020). The EPB guideline recommends a default value of 75 years for the building service life (NMD, 2020).

The main stakeholders for this layer are the architects and engineers who design the modules and decide on the object characteristics as they need to compile the necessary data. Further, the purchaser needs to define what suppliers provide the materials.

Evaluation and Revision

GWH assessed that they possessed the required information of all structural elements and other objects in their houses. The exact material quantities and dimensions, the suppliers, material names and IFC classes were already available. The GFA was currently not available, however, they suggested to calculate it for each module based on the standardized floor plan, and then derive the GFA as the sum of all modules' GFAs. GWH further assessed, that their houses were currently sold for a 50-year service life, and they were unable to guarantee a longer life span. Consequently, they would adapt the building service life to 50 years. The NMD (2020) recommends that adapting the building service life should comply with the guidelines for diverging from the standards provided by W/E Adviseurs (2020).

7.2.6.2 Data Acquisition Layer

Preliminary Design

The data acquisition layer needs to collect the life cycle data of the different objects in the building design. For GWH this data should be collected through the NMD. Further, to make detailed, material-level decisions, the preferred data quality for EPDs is category 1, or category 2 for a lack of availability (see Figure 35). Using specific data sets would also counteract the criticism on the accuracy of the LCA results (Bueno & Fabricio, 2018; Potrč Obrecht et al., 2020). An EPD has a variable validity period of up to five years, with an irregular update schedule that varies for each EPD (NMD, n.d.-c). Consequently, the data needs to be synchronized before each use of the assessment software. The collection of the EPD data is conducted through One Click LCA. The assessment can be further adapted based on data related to the construction site operations to adapt the assessment to GWHs processes (One Click LCA, 2021b). As such, energy use, water consumption, or waste emissions of different processes can be adjusted from the default values, if specific data is available. While this is not mandatory, the company mentioned they would be specifically interested in tracking their waste emissions (see Section 6.3).

The data acquisition of the EPD data itself is conducted independently through external companies and the NMD, thus no technologies from GWH are required for this layer. There are two stakeholders in this layer, first, the NMD, as they collect and verify the EPDs, and control their accessibility. Next to them, the suppliers need to create EPDs of their products according to NMD standards for GWH to use their category 1 EPDs. Hence, there needs to be communication on whether the suppliers have EPDs available, or if they are willing to create them in the future.

Evaluation and Revised Design

GWH reiterated their interest in including construction waste data in the assessment and stated that they were already collecting data on the waste generated during their production process. The default value for waste generation in prefabricated construction is 3% (NMD, 2022), however, GWH was confident to have a lower value. Based on their comments, waste emissions data is integrated into the DTEA. Further, GWH decided to link EPDs to materials through their EPD numbers, which have to be collected to be connected to the BIM model.

GWH estimated that around 30% of their materials currently have EPDs in the NMD, and stated that the availability of EPDs influenced their supplier selection. Additionally, they assessed a high potential to urge suppliers towards creating category 1 EPDs as government initiatives and client interest support the development. Through these comments, it is considered crucial to increase the rate of category 1 EPDs among their materials by working with their suppliers, and increase the focus on EPD availability for supplier selection.

7.2.6.3 Data Transmission

Preliminary Design

The data transmission should connect the collected data to the data analysis, thus concerning the EPDs, and the waste emissions data. A verified calculation tool is needed to access EPDs in category 1 or 2, and thus responsible for collecting the EPD data from the NMD. Of the four currently verified calculation tools, only two advertised a plug-in function on their websites, MPG Toetshulp and One Click LCA (Bimpact, n.d.; One Click LCA, 2022a). Based on the availability of documentation and transparency about the processes, the DTEA was focused on using One Click LCA. The waste emissions data is expected to need manual transmission to be entered into One Click LCA project data (One Click LCA, 2021b), as no information on an automated transmission was found.

As already defined in the data acquisition layer, the irregular updates to the NMD require the transmission of relevant data before each assessment, thus the transmission frequency is dependent on the assessment frequency. Apart from transmitting the EPDs, there is a need to transmit information about the changes to EPDs through the calculation tool. It needs to inform them of changes relevant to their projects, and highlight the impact on the assessments of their projects. Due to their relevance in this transmission process, the software provider is a stakeholder, and they need to ensure their software has continued access to the newest data in the database.

Evaluation and Revision

In the evaluation, GWH mentioned that Koopmans was already using the MPG Toetshulp tool from Bimpact B.V., and that the program was not fulfilling GWHs expectations. Consequently, the focus on One Click LCA is reinforced. The interest in this software was validated during a meeting including a demonstration of the tool and its features. An important requirement to GWH in this transmission process was being informed of changes to EPDs included in their projects. One Click LCA confirmed that their software would fulfil this requirement (C. Aittokallio, personal communication, 20/12/2022). Additionally, the software warns the user about data sets that will soon be updated (One Click LCA, 2022b).

7.2.6.4 Data Storage & Digital Model/ Information Layer

Preliminary Design

The data storage and digital model/information layer needs to create, preprocess the collected data and store it. Further, it needs to create or adjust any models incorporated into the DT. The dynamic data need for this phase includes the EPD data, and potentially also the construction waste data. The static data includes data in the physical layer needed for the BIM model. Further, the GFA and building service life need to be available and stored for the data analysis. In this case, little preprocessing is required, as the EPD data is already prepared through the NMD. The waste data might need preprocessing to fit the data format required by One Click LCA.

The modelling process needs to construct a BIM model of LOD 300+ by incorporating the data from the physical layer. The object-related data needed by the software is the IFC class, the material name, the quantity in a recognized unit, and the dimensions (One Click LCA, 2023b). The dimensions are only necessary for scalable products, otherwise they are disregarded in favor of the default values. The information should be formatted in the NLsfb semantic standard for BIM, which One Click LCA recognizes and interprets for the data import from BIM (One Click LCA, 2021d).

The information model also needs to prepare the connection between the BIM model quantities and the EPDs. To use the EPDs from the NMD, each material quantity has to be connected to a fitting EPD within the database. This process is called matching. This specific process should be automated to fulfill the requirement. One Click LCA provides various techniques to connect the materials directly to an EPD, which are summarized in Table 18. Next to direct matching techniques, there is also a possibility to teach the system how to map the materials, by manually matching them in the beginning, and then letting the system learn how to match them in the future (One Click LCA, 2023b).

Table 18: Matching Techniques to Directly Link Materials to EPDs in One Click LCA

Technique	Description
Full Name	Copy the EPD material name to the BIM material name field, connects to the newest dataset matching the description, but might cause conflict with duplicate names.
One Click LCA ID	Create a field named 'OCLID' and use the provided ID. This ID refers to one specific data set, and will not update once there is a newer dataset.
EPD number	Create a field named 'EPD number' which connects it to the dataset with the same EPD number, this will update to the newest data set, but it can only be used for actual EPDs.

The design and object information can be stored in the BIM models. However, establishing a personalized BIM object library for GWH with predefined materials for their designs could assist in the automation process and ease future design workflows (Hollberg et al., 2020). The data for the building service life and the GFA is not object-specific, thus another storage for the data is required. Similarly, any data related to construction site operations has to be stored separately. The EPDs are stored in the NMD database.

Based on the processes in this layer, the technology includes a BIM software for the modelling, and an LCA software for connecting the modelling results to the EPDs. The two software should also be interoperable, to facilitate a direct data connection and enable the plug-in feature. As the LCA software to be used was defined as One Click LCA, the chosen BIM software needs to be interoperable with it. One Click LCA promotes that 15 BIM software are directly compatible with their programming (One Click LCA, n.d.-a). The supported software include Autodesk Revit, IES-VE, Tekla Structures, Tekla Structural Designer, Trimble Connect, Rhino & Grasshopper, Bentley iTwin Platform, DesignerBuilder, Autodesk 360, Bentley OpenBuildings Designer, IFC – Industry Foundation Classes, Simplebim and Naviate Simple, StruSoft, ArchiCAD, gbXML, Autocase, SketchUp Pro, and IDA ICE (One Click LCA, n.d.-b). However, the level of interoperability with each software varies, from the ability to perform Excel-based exports, to data export plug-ins linked directly to their web-application, to fully developed tools with in-software assessments. Further, the ability of each BIM software to support the design requirements, such as the NLsfb formatting and plug-in capabilities, and to provide the necessary modelling features needs to be considered. The only software with a fully developed plug-in to facilitate an assessment within the BIM software was Autodesk Revit. Yet, IES-VE, Tekla Structures, Tekla Structural Designer, Trimble Connect, and Bentley iTwin Platform exhibited rudimentary plug-in functions to export the BIM model directly to online applications of their software.

The stakeholders in this layer include One Click LCA as the LCA software provider, that needs to ensure the interoperability between their software and BIM software. Further, there is a need for modelers to design, maintain, and update the BIM models for GWH.

Evaluation and Revision

GWH assessed that they used elaborate BIM models, yet their current models did not include all necessary data for the LCA assessment and would need to be adapted. Material quantities were available, but split between a structural model, a façade model, and an installations model. The suppliers and IFC classes are known, but not yet integrated into the model. Further, GWH did not have modelers available to develop and adjust the models to the needs of the LCA process, which caused them to outsource the modelling process.

Regarding the EPD matching techniques, GWH evaluated that the ‘full name’-technique was not compatible with their current naming system that connects to their ERP system and purchasing process for their suppliers. Further, the ‘One Click LCA ID’-technique did not support an automatic update to the newest data set after EPD data changes, which would not suit their aim for automation. Thus, the ‘EPD number’-technique will be used to match the EPDs. This will require collecting the EPD number for each material and integrating the data into the BIM model as described in Table 18.

GWH stored the BIM models in the Autodesk 360 cloud and expressed a desire to develop a personalized BIM library for their design elements, which was not yet available. Further, their BIM models were created externally in Rhino & Grasshopper and then converted to IFC models for GWH. They were interested in switching to another BIM software and eliminating any data loss caused through the IFC conversion. Based on a meeting with One Click LCA, they preferred the Autodesk Revit software due to its interoperability with One Click LCA and its proficiency in structural modelling.

7.2.6.5 Data Analysis/Knowledge Engine Layer

Preliminary Design

The data analysis/knowledge engine layer for the BIM-based LCA assessment carries out the LCIA and calculates the final impact based on the EPB calculations defined by the NMD (2022). To connect the assessment to the NMD it is carried out through the LCA software One Click LCA. First, the software needs to import the material quantities from the BIM model, which is possible through an Excel file, gbXML file, or a software plug-in (One Click LCA, 2022a). This process will use the plug-in and acquire the data directly through the BIM model, according to the design requirements. Thus, when activating the plug in, the data extraction is automatic. When all the BIM model data requirements for the import process (see Section 7.2.6.1) are fulfilled, the quantities are automatically linked to the EPDs and the LCA can be calculated. Next to the BIM model input, the project parameters need to be checked and adapted if necessary. This includes the GFA, which needs to be manually entered for each project (One Click LCA, 2022d). Further, the building service life, which has a default value of 75 years for residential buildings, but needs to be manually adjusted for possible changes (One Click LCA, 2021a). Lastly, the construction site operation parameters are set at their default values, but can be changed if desired (One Click LCA, 2021b). The software automatically assesses the EPB and provide the results in €/m2/yr (NMD, 2021b).

In this process the software provider is a stakeholder, who ensures their tool carries out the process correctly. Further, the NMD is involved in validating the software. The necessary technology is the LCA software and the interoperable BIM software. Further, as the process relies on cloud storage for all input data, and data transmission speeds are not relevant due to the lack of real-time assessments, cloud computing is recommended.

Evaluation and Revision

The data analysis layer requires little decision-making from GWH. Additionally, they were unsure, whether a, LCA expert might be required to conduct and validate the assessments for legal purposes in the future. However, the impact of this possibility on the assessment of the environmental performance to make material choices should be evaluated.

7.2.6.6 Service Layer

The service layer should interpret the results, present them to the users, and create a feedback loop. The process part of the service layer should interpret the results of the LCIA and draw conclusions, that can then be presented to the users. The RVO (2021b) has recommendations for interpreting the EPB score of a building, e.g. determining the contribution of different materials and life cycle phases, and determining the influence of factors like the GFA. Thus, the results should be presented in sufficient detail to enable these assessments. These types of aggregations are available within their assessment tool, or the results can be downloaded via Excel and checked externally (One Click LCA, 2020b, 2021c). An Excel download is to be conducted upon the conclusion of a project, to fix the result and prevent changes to the assessment in the future. Next, the service layer should be able to compare two different designs. This would require the LCA assessment of another design.

The service layer needs to present the results through a dashboard, that allows them to make material level decisions, compare different designs, and present the results to the clients. To make material level decisions, the results need to be presented to the responsible engineers. The comparison of different designs can be both directed at GWHs needs, to compare their design ideas, as well as to the clients' needs, to show them the impact of different design decisions. The visualization process will be automated by using One Click LCA to format them. One Click LCA offers options to format the results according to different needs and create various visualizations of them in graphs and tables (One Click LCA, 2020b). Further, they offer options to compare different materials and designs and visualize the results (One Click LCA, 2020a). Additionally, the One Click LCA software offers a visual representation of the results within the BIM model for Autodesk Revit, using color overrides to display the total or relative impact of different elements (One Click LCA, 2023a).

Lastly, there is a feedback loop, that uses the decisions to make changes to the design. In this feedback loop the decisions made by GWH engineers and clients are implemented. This entails updating the BIM model both on a project and product level. This feedback process requires human intervention to convert the decisions into design changes in the BIM model. Thus, this DT design would be classified as a passive DT. In the feedback process, the main stakeholder are the engineers at GWH responsible for the BIM models and their maintenance. Further, the process requires access to a BIM software. This software should be aligned to the software used in the previous modelling process.

Evaluation and Revision

GWH stated they did not want to conduct the statistical assessment of the results in the standards proposed by RVO (2021b). For the time being, they would like to focus on other processes, including creating their own benchmarks for their houses. For the design comparisons, they decided that for themselves they want to compare different materials for specific parts and see how these changes could improve their environmental impacts. Further, they want to offer clients comparisons of design options, which include a range of different scenarios that make particular changes to the standardized product design. GWH suggested that different scenarios could be e.g. a carbon neutral scenario, a bio-based material scenario, or a circular building scenario. Additionally, they amended that a comparison in cost would need to support the decision-making. Consequently, these alternative scenarios need to be defined and the cost estimates gathered for the decision-making.

GWH highlighted that the main user of the results for GWH would be the product developer, who could make design decisions and change production processes. Any change of production processes was estimated to influence the waste emissions of GWH. Regarding the interfaces, they identified the need to have a quick overview of the results for their different scenarios, whereby the results should be separated for different building layers. They approved of the visualization options that One Click LCA presented to them in a meeting, and would like to look into them more for the interfaces.

7.2.7 Strategic Advice for a BIM-Based LCA DT for GWH

Based on the DTEA, recommendations for the further steps in DT development are derived. The resulting recommendations are summarized in Figure 38 and Figure 39. Each layer's box is colored to indicate the current state of the layer and give a quick overview on what layers need the most work to be functional. The colors correspond to Figure 32 (see Section 7.1.5).

The overview shows that the most important layer to focus on is the data storage & digital model/ information layer. It is important to commit to the integration of relevant data into the BIM model, as the current model would not enable an automatic assessment. Additionally, to promote automation in the design process and ensure the consistency of data in the model, a personalized BIM object library containing all relevant characteristics can be created (J. P. Carvalho et al., 2021). Another important aspect to implementing the DT design for GWH is acquiring interoperable software that can conduct the assessment through an automated connection. The important software tools are a BIM software and an LCA software, and the DTEA established that using the Autodesk Revit software in connection with the One Click LCA tool would yield the most benefits to GWH. This includes the use of a plug-in for the BIM software, automated EPD matching, the compatibility with the NMD and the NLsfb format, as well as the capacity to visualize and report the results in adjustable formats.

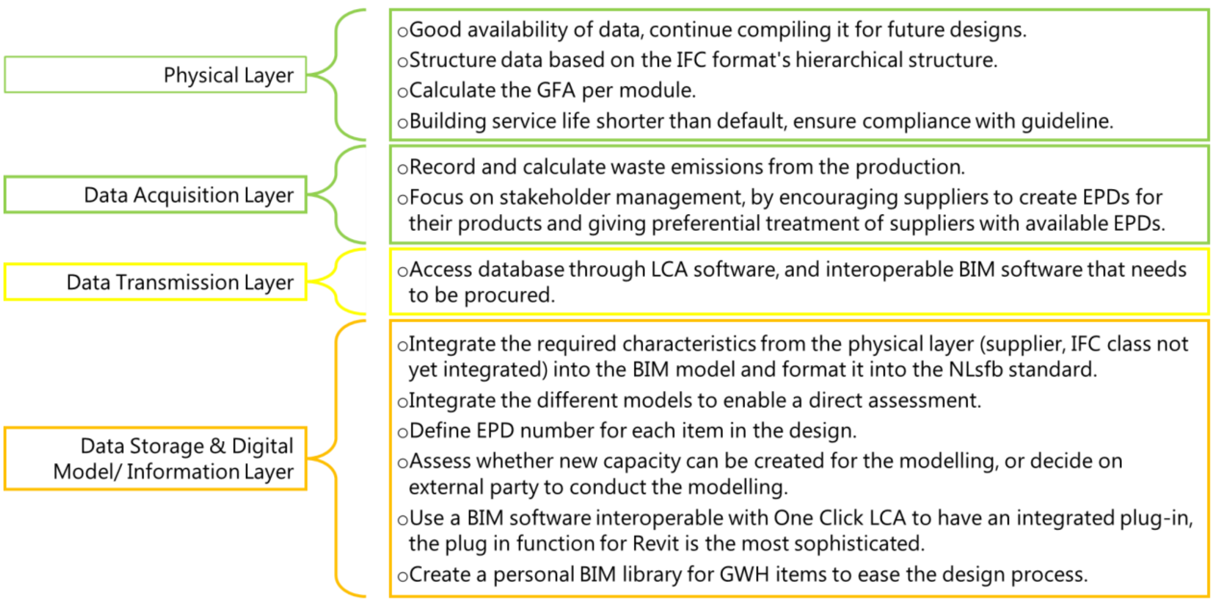


Figure 38: Strategic Recommendations for the Development of a BIM-Based LCA DT for GWH (1)

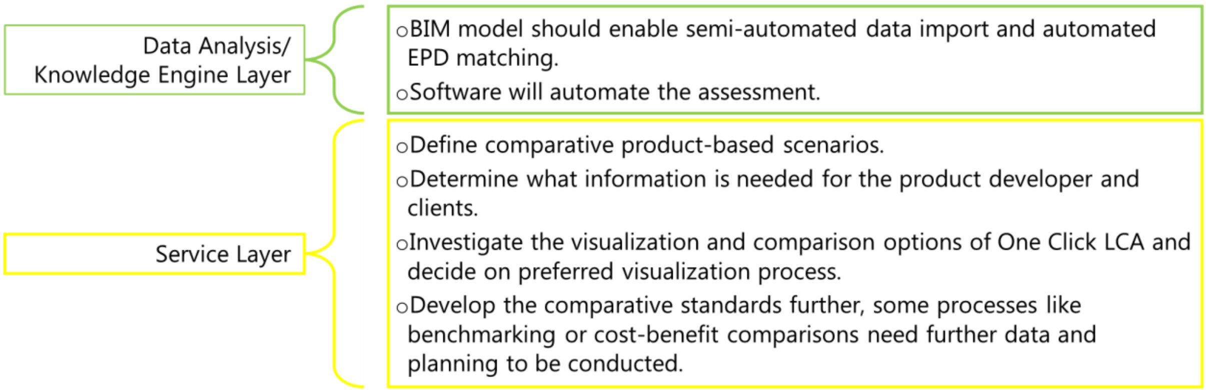


Figure 39: Strategic Recommendations for the Development of a BIM-Based LCA DT for GWH (2)

7.3 Conclusion

This chapter addressed the fourth research question, and developed strategic recommendations for GWH regarding the development of a building energy benchmarking DT and a BIM-based LCA DT. The process of creating these recommendations followed the first four phases of the design science approach outlined in Figure 6, which conducted the demonstration of the artefact by developing the recommendations according the gap analysis outlined in Figure 11.

The recommended DTEA for a building energy benchmarking DT is visualized in Figure 30, with more detailed descriptions in Appendix D: Descriptive DTEA Energy Benchmarking. The strategic recommendations derived for the demonstration are shown in Figure 33 and Figure 34. It was found that the data analysis/knowledge engine layer needed the most attention. Especially the benchmarking process should be decided on in cooperation with an expert in that domain, but an artificial neural network was found to be most promising. Also, the service layer needs further attention, as the intentions for using the benchmarks were not certain yet. All other layers are partially present, yet further development should be focused on the pre-processing of data and the creation of a physical energy consumption model to identify the noisy factors.

The recommended DTEA for a BIM-based LCA DT is shown in Figure 37, with more detailed descriptions in Appendix E: Descriptive DTEA BIM-Based LCA. The strategic recommendations derived for the demonstration are shown in Figure 39. They found that the development of a BIM model that contains all the information necessary for the assessment is important. Further, the use of a verified LCA software is crucial for conforming with national regulations, and to equip the data analysis and data transmission layers. Lastly, more development is required to structure the intended feedback processes. Additionally, it was found that the development of a BIM library could aid in the automation of the processes by supporting the conformity of the models.

The implementation of the framework also revealed potential revisions for the DTEA and the process for deriving recommendations. A major revision is needed for the physical layer, as it was found that the characteristics of the considered entities are also of importance to the layer. This might concern any static information about these elements that is important to the further process. In this study examples for characteristics added were the floor area of a house, its service life, the type of installation or house considered, or the material specifications needed for a BIM model. Another major finding relates to the feedback loop. While it is always considered important that a DT has a connection back to the physical layer, it was also found that feedback can also connect to other aspects of the DT structure, for example by improving the models or the data analysis algorithms. Thus, also digital system internal feedback loops are possible.

The application of the gap analysis process showed that the gap analysis process planned in Figure 11 did not yield satisfying results. Thus, this process was adapted in this research to include an evaluation and allow GWH to make decisions and revise the DTEA before comparing it to the current situation. As any design revision might reveal further decisions to be made, it might be required to have several evaluations with the company between to produce an optimal design. As this was found to be necessary for the development of both DTEAs, it is recommended to adapt the process to feature an iterative process in general to include the stakeholder(s) in the design decisions where necessary. Further, the process showed that it might be necessary to design the process to be automated by the DT before designing each element, as these overarching decisions can influence the structure of the DT. For example, the LCA requires the setting of a goal and scope, which does not relate to a specific element, but is a necessary step in the development of an LCA, and thus also a DT for conducting an LCA. Similarly, the building energy benchmarking required the planning of the benchmarking process before its adaption in the DT.

Next, the resources used to design the DTEA was very different for the two DT uses in the case study. While the energy benchmarking DTEA was largely designed based on the findings in scientific papers, the BIM-based LCA DTEA was largely based on the regulations and information from practice-based sources. While the scientific papers offer more design freedom, there is a lot more guidance in the use of regulations and practice-based information, which limits the number of decisions for the stakeholders by precluding many decisions.

Another finding was that while a generic design of the DT elements was possible, including a more detailed planning was hindered through a lack of specific knowledge for the practical aspects of the DT. Thus, developing a more detailed planning would require specific domain knowledge. This is shown especially in the energy benchmarking DTEA, where a benchmarking method in the data analysis layer can be reasoned for, but domain knowledge is recommended for the further development. Another example is the development of the technology elements. While a general technological structure could be estimated, the detail of the elements could be increased by more specialized knowledge on the technological components needed.

8 Evaluation of the DT Development Framework

The last step of the design science approach is the evaluation of the DTEA framework and its results. Thus, this chapter aims to conduct the evaluation and validate the framework and its results. The evaluation process is described in Section 3.2.2.4 (Step 5). First each DT use is evaluated based on an informed argument and the focus group evaluation criteria (Table 3). Lastly, the framework is further assessed through open questions. The results are used to revise the DTEA framework.

8.1 Energy Benchmarking Results Evaluation

8.1.1 Informed Argument Evaluation

The detailed argumentative evaluation of the energy benchmarking design requirements can be found in Appendix F: Informed Arguments for Building Energy Benchmarking Evaluation. It shows that all requirements were all addressed in the planning of the energy benchmarking procedure and then further implemented in the DTEA. Thus, the DTEA is validated for its design requirements.

8.1.2 Focus Group Evaluation

The evaluation of the case study results for the development of an energy benchmarking was conducted on 13/02/2023 and all citations in this section originate in this session. Table 19 summarizes the ratings of the five criteria and supports them with relevant quotes from the discussion.

Table 19: Evaluation Energy Benchmarking DT Results

Criteria	Evaluation	Comments
Reflection of priorities	Moderate	'I think it is important to add the different goals of the energy benchmarking. Because […] with comparing it to the theoretical calculations, I think with that added it comes very close.' - Project coordinator
Integration into company structure/ process	Low	'It is so much coordination. It seems very easy […], but [the effort] is quite high, especially for a company that has a focus on making modules'- Project coordinator
		'Someone must be owner of the data and be able to interpret it against calculated values. For that you have to have some knowledge and you have to get some people on it to identify the data that is coming in, and we don't have that right now' – Building Physics Expert
		'This […] needs to be discussed on a different level, to make a decision on what we want to invest to get this into place. And there are more entities, like TBI, Koopmans. We don't talk to end users as geWOONhout, we don't have a contractual relationship with the customer' – Director GWH
		'You need to organize this at the TBI level' – Director GWH
		'It does fit the strategy, it does not fit the structure right now' - Trainee – Digital Twins
Overview of possible DT elements	High	'for me it gives a clear overview of what you need to implement' – Trainee – Digital Twins
		'I agree, also with the additions we made' - Director GWH
		'there are two levels on it, […] on a strategic level it is a very good framework to have an overview, if you have it on an operational level, then it is not detailed enough' – Project coordinator
Implementation planning	Moderate	'needs some steps to make it directly outlined, but it is helpful in outlining to give a direction' – Project coordinator

Criteria	Evaluation	Comments
		'your research mainly focuses on the preparation, but for the operation it would not be detailed enough' Trainee – Digital Twins
Sustainability connection	Moderate	'it is difficult as to what is our goal, because our goal is not to make a very energy efficient house [...], that is not directly our goal, it helps us in our goal' – Project coordinator
		'it does not have to do with your framework, it is just because our company has not directly that goal' – Project coordinator

The reflection of the company's priorities was said to be moderate. In general, it did reflect their priorities, but there were certain aspects they felt were still missing in the recommendations, e.g. a comparison of theoretical data to their collected data. The integration of the recommendations into the processes of the company was rated low. They thought that the idea of having an energy benchmark corresponds well to their goals, however, its implementation was too complicated for their means. Further, they assessed that its integration would require a discussion on a different organizational level, preferably the TBI level. They further reflected that they gained a very clear overview of the elements based on the DTEA, thus rating this criterion as high. They did specify that a clear overview was only achieved on a strategic level, but they would need to be specified for the implementation at an operational level. Further, they reflected that this operational level would be eventually required for the practical implementation. Similar feedback was given for the ability to plan the implementation, which was rated as moderate. It was assessed that it would provide a direction but was lacking in detail to plan it out for operation. Lastly, the connection to the sustainability goals was thought to be moderate. They highlighted that while the recommendations would fulfill their purpose, but their goals are not directly related to energy use, just being supported by it.

Further feedback was given on the content of the recommendations. Consequently, they commented that separating the data analysis from the benchmark type, could enable connecting the data analysis process to several different goals. Further, they indicated that they gained insight on how to implement the DT, but not on how to use the results to market DT implementation to their superiors and advocate for it. This 'focus on future possibilities' (Director GWH, personal communication, 13/02/2023) would elevate the research results to a higher level for a company.

8.1.3 Conclusions from the Energy Benchmarking Evaluation

In summary, the feedback on the energy benchmarking results was mainly positive, supporting that the framework was able to give a clear overview of the elements involved, and moderately successful help GWH to plan implementing a DT and to achieve their sustainability goals. A major takeaway from the feedback is that there are different levels of detail for the DTEA and its design. The DTEA was designed on a strategic level, however, GWH thought that developing it on an operational level would ease the implementation planning for them.

Despite the positive feedback, they assessed that the strategy did not fit into their processes, and consequently does not address this aspect of the research problem. Their feedback suggested that the decision-making process for the implementation needed to be on a higher level than their own company. The current focus was on stakeholders for the implementation of a DT based on its functions, but their inclusion based on the decision-making structure of the company could also be relevant. This might require analyzing a company's processes also on an external level.

8.2 BIM-Based LCA Results Evaluation

8.2.1 Informed Argument Evaluations

The detailed argumentative evaluation of the design requirements is shown in Appendix G: Informed Arguments for BIM-Based LCA Evaluation. It shows that all requirements were all addressed in the planning of the BIM-based LCA process and then further implemented in the DTEA. Thus, the DTEA is validated for its design requirements.

8.2.2 Focus Group Evaluation

For the evaluation of the BIM-based LCA DT results, the recommendations were presented in the focus group session on 13/02/2023. However, due to time restraints the evaluation of the criteria had to be done individually and could only be conducted with three of the four participants. The criteria were rated in interviews by Project coordinator (13/02/2023) and Trainee – Digital Twins (16/02/2023), and via email by Building Physics Expert (01/03/2023). Figure 40 shows the ratings of the participants. The median of the results is used It represents the score of each participant as a number between 0-3, with 0 signifying a rating in the low category, and 3 signifying a rating in the high category. Further, Table 20 gives an overview over comments made by different participants during the evaluation.

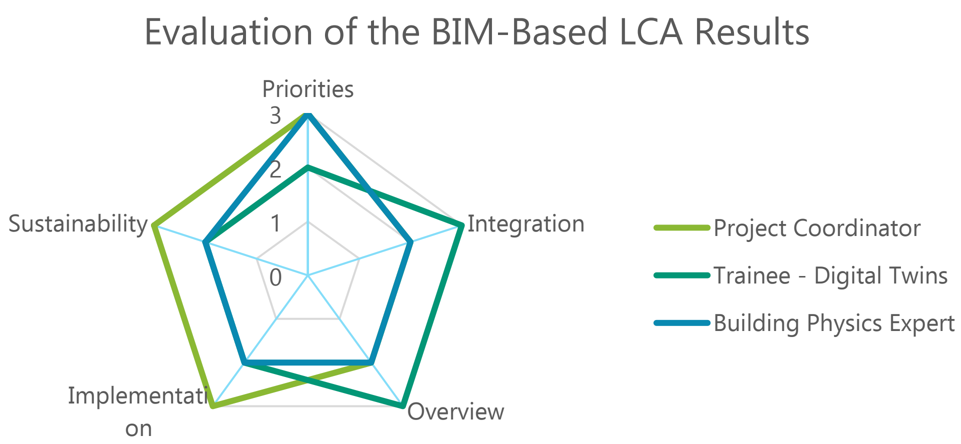


Figure 40: Evaluation Scores BIM-Based LCA Results

Table 20: Evaluation BIM-Based LCA DT Recommendations

Criteria	Rating	Comments
Reflection of priorities	**Mostly high**	'this one is very close to the strategy' – Project coordinator
Integration into company structure/ process	**Mostly moderate**	'it fits really well into our business model, I think in a perfect world we would have this 3D model and all requirements from production but also from One Click LCA, if we have a good structure it falls into all other software models and we don't have to do anything anymore' - Trainee – Digital Twins
		'we already have so much organized and the process is so far, and we already have a product development department. If we put the right information in the models, [...] then it is quite easy' – Project coordinator

Criteria	Rating	Comments
Overview of possible DT elements	**Mostly moderate**	'the structure is very clear' - Trainee – Digital Twins
Implementation planning	**Mostly moderate**	'It lacks the part where we go from the set-up to where we actually do it' - Trainee – Digital Twins
Sustainability connection	**Mostly moderate**	'It helps us to develop to a more sustainable product, […] but the DT in itself does not make us more sustainable' - Trainee – Digital Twins
		'In your feedback loop there is a human making a decision between money and sustainability' – Trainee – Digital Twins

For the BIM-based LCA recommendations, there are three scores for each criterion. The participants rated all categories between moderate and high, making the feedback highly positive. The reflection of priorities was on average scored high. The DTEA was considered to reflect the functions they had envisioned very accurately. All other criteria were each rated moderate on average. The integration into the company processes was considered to be 'quite easy', though they would need to adapt the modelling process at the product development level. However, it was also seen as a challenge to adjust 'the BIM models in such a way that a direct link to LCA data is possible' within the LCA software (Building Physics Expert, personal communication, 01/03/2023). It was also found that the DTEA gave an overview of the elements included. Again, increasing the specificity to an operational level was seen as a way to improve the result. The strategy was estimated to help the company outline the implementation of the DT. Especially the overview of the BIM model and the detail it should have was seen as useful for the planning (Project coordinator, personal communication, 13/02/2023). However, the need for an operational level of detail was once again mentioned. Lastly, the sustainability connection was seen as strong, as it was directly aimed at the goals of GWH (Project coordinator, personal communication, 13/02/2023). However, it was also remarked that sustainability improvements were not inherent, but dependent on how the DT was used. Thus, there was a requirement for someone to make a 'decision between money and sustainability' (Trainee – Digital Twins, personal communication, 16/02/2023). As other factors would affect this decision, sustainability improvements could not be guaranteed. other data related to the production processes too.

8.2.3 Conclusions from the BIM-Based LCA Evaluation

In summary, it was found that the DTEA and recommendations were able to satisfy the design requirements and received positive feedback through the focus group evaluation. Thus, the evaluation validated the use of the framework for the intended purpose. The evaluation of this DT use reiterated the idea of an operational level that was more specific than the current one, which would aid in the implementation of the DT into practice.

8.3 Open Questions

The third part of the evaluation takes a more in-depth look at the theoretical framework in general to identify improvements. To this effect, each focus group participant was asked the same four questions, which are meant to give them the opportunity to freely give their feedback on the framework. This section reviews their answers and draws conclusions from them.

(1) What are the benefits of having this overview for the implementation of a DT?

A selection of relevant quotes from the answers received is shown below.

"It's helpful to structure it to see where we should invest time and attention" (Trainee – Digital Twins, personal communication, 16/02/2023)

"Good analysis of how we are doing on those points" (Trainee – Digital Twins, personal communication, 16/02/2023)

"Structure them really well in order to see where problems are" (Trainee – Digital Twins, personal communication, 16/02/2023)

"Provides an overview of the necessary elements and the step-by-step plan to implement them" (Building Physics Expert, personal communication, 01/03/2023)

"Not only focusing on the results, […] with the use of this framework you are also asked to think about the data. […] Also, [it has] these kinds of levels that are more about how to get the data." (Project coordinator, personal communication, 13/02/2023)

"That it is guided by steps [to find] which data you need and what you lack" (Project coordinator, personal communication, 13/02/2023)

"What really helped was that you gave the background of the framework, and […] also the information behind the [DTEA]." (Project coordinator, personal communication, 13/02/2023)

"To think about where it is close to the strategy and the targets in the company" (Project coordinator, personal communication, 13/02/2023)

All participants saw the framework as beneficial for their planning efforts. Both the ability to identify and structure information related to DTs was praised, especially as it goes into depth and also identifies the underlying data needs for the data analysis. Also, the use of guiding questions for identifying the necessary elements was perceived to ease the use of the framework for companies, as they can get a better understanding of what each layer means and what aspects are important to consider. Additionally, the gap analysis method was perceived beneficial, as they thought the comparison to the current situation allowed them to single out the aspects where work is needed. Especially, as they can identify how to invest their time and attention to get to the desired results. Another benefit discovered was the possibility to connect the DT planning to the targets of the company and fulfil their goals.

The results of this question show that there are benefits to this framework perceived by the company, and it can be concluded that the approach taken to develop the recommendations for the company was successfully employed in this case study.

(2) What do you see as major challenges for the implementation of the recommendations?

A selection of relevant answers to the question is shown below.

"I see a lot of difficulties especially regarding the analysis part" (Trainee – Digital Twins, personal communication, 16/02/2023)

"The results of what we are going to sensor must answer some business question, it is really easy to install some sensors in a building, […] but it is really hard to get some conclusion out of it which is insightful for other parts of the company or for improving the product." (Trainee – Digital Twins, personal communication, 16/02/2023)

"[We] are production-focused and don't have time to make a good analysis" (Trainee – Digital Twins, personal communication, 16/02/2023)

"Adjusting the BIM models in such a way that a direct link to LCA data is possible" (Building Physics Expert, personal communication, 01/03/2023)

"To make your work easier by using the machines, you have to learn how the machines are working. [...] Therefore, you sometimes have workshops to learn it by yourself. But then you also have to make it part of your job to use it, and that makes it very difficult. That you steer people [towards] using the DT. We understand it will help in our job, but it is difficult to implement in our jobs. That asks especially the willingness of people to incorporate it to their business." (Project coordinator, personal communication, 13/02/2023)

The answers of the participants show that there are still a range of issues that hinder the implementation of DTs for GWH. One aspect that came up with all participants, was the lack of work time capacity that workers have to learn about DTs and include additional work steps for DT implementation in their processes. This issue also relates to the findings in the goals of GWH, where they were strongly aiming toward automating the processes in the DT with as little additional work for their employees as possible. Thus, the additional work steps and time for workers is an important part of planning DTs and should be considered in the design of an implementation plan.

Another answer was related to the knowledge about how to use the results, as using the conclusions of the DT might be difficult to plan. Additionally, the willingness of businesses to integrate DTs was seen as a difficult aspect. This was also shown in the DT uses evaluation, where e.g. the automated multi-parameter design optimization was seen as helpful to sustainability, but the results would be too restricting for GWH. Similarly, automated sustainability rating schemes were seen as feasible, but the potential to use the results was seen as restricted due to the lacking interest from clients. Consequently, considering the usability of the results and helping companies identify these uses could help companies in developing DTs.

(3) What value does it have to consider stakeholders in the framework?

A selection of relevant answers to the question is shown below.

"Highly. Every stakeholder should benefit, so that they cooperate in making it possible" (Building Physics Expert, personal communication, 01/03/2023)

"Nothing is all about technique or data, but you always depend on humans in your plans" (Trainee – Digital Twins, personal communication, 16/02/2023)

"Because they have quite a lot of impact on how easy it will be – or won't be – to incorporate the DT. [...] It is important to incorporate those people or companies which have an impact on the goal you want to reach, and therefore it is important to look for stakeholders." (Project coordinator, personal communication, 13/02/2023)

"Maybe it is better to also do a stakeholder analysis, to see which specific thing they impact in the DT? Then you also know what you need to do with the stakeholder." (Project coordinator, personal communication, 13/02/2023)

The answers of the participants validated the importance of stakeholder planning in the DTEA, mentioning how important it is to involve stakeholders to ease or enable the implementation of the DT. It went even further to suggest expanding the depth of the analysis, for example by incorporating a full stakeholder analysis to identify the exact aspects the stakeholders influence and how to best address them to achieve the optimal results. Thus, this section concludes that the addition of stakeholders to the framework was beneficial and should be focused on further in the future development of DTs.

(4) Are there any elements you think the framework was lacking?

In this questions most answers related to the same issue, that is summarized in the follow quote:

"To give it a good purpose for companies, it lacks the final part, [...] of what we are going to do with the data that comes from the DT" (Director GWH, personal communication, 13/02/2023)

This issue was raised several times throughout this evaluation. First in the evaluation of the energy benchmarking recommendations, then regarding the challenges for implementing DTs. Consequently, this was seen as an overarchingly important aspect to companies, which uncovers an important aspect that hinders them in implementing DTs. Consequently, this aspect needs to be addressed in future research regarding DTs.

8.4 Conclusion and Recommendations of the GWH Evaluation

The evaluation of the results was positive for both DT uses, and the framework was seen as helpful to the planning and future development of a DT. The evaluation highlighted specifically the overview given through the DTEA, the ability to structure its elements, the inclusion of stakeholders, and the questions behind the descriptive DTEA.

However, there were also different aspects that could be improved to give a better access for companies to the DT planning. First, the interest in more specific recommendations was highlighted. It was suggested that the development of an overview and recommendations on an operational level would aid the implementation of a DT. Consequently, the development of a more detailed DTEA on an operational level should be carried out in future research.

Another aspect mentioned was the expansion of the stakeholder aspects and the addition of a stakeholder analysis to increasingly focus on the treatment and inclusion of different stakeholders. Further, the review of the energy benchmarking recommendations showed a lack of consideration for important stakeholders. Based on these findings, it is recommended to conduct further research on what stakeholders should be included in the planning and what information about these stakeholders is needed, to develop an improved assessment of stakeholders for DT development.

Lastly, the research showed that structuring and identifying DT elements can help, yet if there is uncertainty about how to use the results to create value for the company, it is difficult for a company to implement. Consequently, it is recommended to expand the planning structure to not only focus on the elements of the cyber-physical system, but also the different opportunities and benefits its implementation can bring to the company.

9 Revision of the Theoretical Framework

This chapter aims to use the insights of the case study and its verification and validation processes to improve the theoretical framework created in Chapter 4. First, it will look at the DTEA, and then at the process for deriving the strategic recommendations.

9.1 Revised Digital Twin Element Architecture (DTEA)

The DTEA was created to identify the elements of a DT, structure them and define them for a specific DT use. The case study implemented the DTEA and descriptive DTA (see Figure 9 and Table 4), and discovered the potential for improvements in four distinct areas, (1) the physical layer, (2) the feedback connections, (3) the assessment of stakeholders, and (4) the integration of value/benefit considerations. Based on the findings, a revised DTEA and descriptive DTEA are proposed in Figure 41 and Table 21.

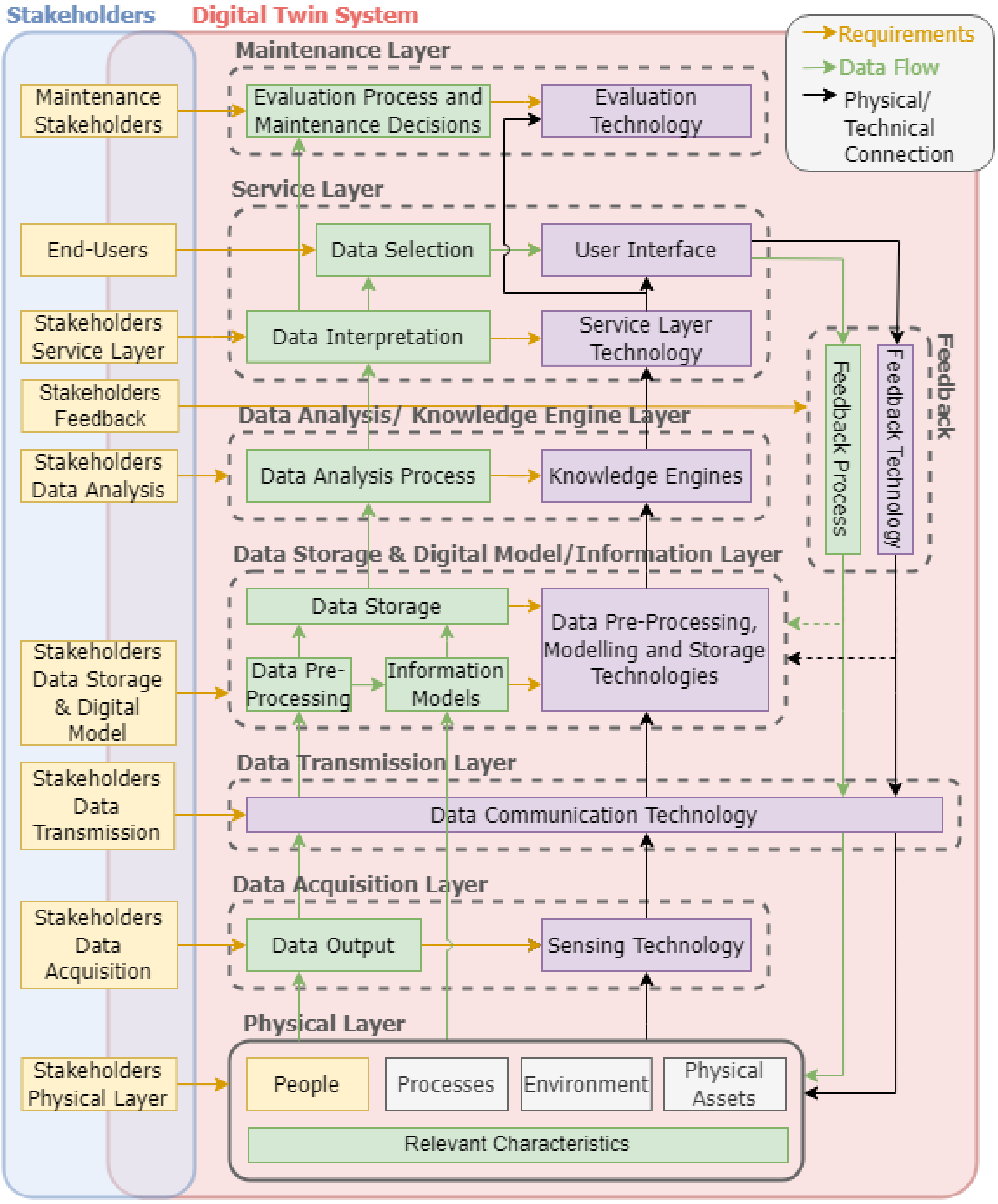


Figure 41: Revised DT Element Architecture

Table 21: Revised Descriptive DT Element Architecture

Layer		Stakeholders	Data	Technology
Maintenance Layer		What stakeholders are relevant to this layer? What decisions do they make? What competencies do they contribute? What data do they contribute? What is their power on and interest in the DT? What strategy should be used to engage them?		
Service Layer	Users	Who are the user(s) of the DT?	What information is of interest to the user(s)? What is the value of the recommendations/information to the user?.	What type of interface should be created for the user? How should the information be visualized?
	Process	What stakeholders are relevant to this layer? What decisions do they make? What competencies do they contribute? What data do they contribute? What is their power on and interest in the DT? What strategy should be used to engage them?	What decision-making process is supported? What insights are needed to support these processes? What information/ recommendations are the output of the process?	What technologies can aid in interpreting the insights?
	Feedback	What stakeholders are relevant to this layer? What decisions do they make? What competencies do they contribute? What data do they contribute? What is their power on and interest in the DT? What strategy should be used to engage them?	What feedback is communicated back to the physical layer? How will the feedback be implemented? Is the DT active or passive?	What technologies might support the implementation of the feedback?
Data Analysis/ Knowledge Engine Layer		What stakeholders are relevant to this layer? What decisions do they make? What competencies do they contribute? What data do they contribute? What is their power on and interest in the DT? What strategy should be used to engage them?	What insights should the data analysis create? What data analysis process needs to be conducted to achieve them?	What KEs can support the data analysis process? What computational structure should the DT use to access the data storage?
Data Storage & Digital Model/Information Layer		What stakeholders are relevant to this layer? What decisions do they make? What competencies do they contribute? What data do they contribute? What is their power on and interest in the DT? What strategy should be used to engage them?	How should the dynamic data be pre-processed? What models contain the static data? What LoD should these models have? How is dynamic data integrated into these models? What data storage is needed for the data?	What technology is required for the data pre-processing? What technology is required for the modelling? What technology is required for the data storage?

Layer	Stakeholders	Data	Technology
Data Transmission Layer	What stakeholders are relevant to this layer? What decisions do they make? What competencies do they contribute? What data do they contribute? What privacy rights need to be considered? What is their power on and interest in the DT? What strategy should be used to engage them?		What data transmission technology can be used? What are the requirements for the data transmission (range, energy consumption, data type, communication frequency, reliability, security)?
Data Acquisition Layer	What stakeholders are relevant to this layer? What decisions do they make? What competencies do they contribute? What data do they contribute? Who owns the collected data? How can the data be secured? What is their power on and interest in the DT? What strategy should be used to engage them?	What data needs to be collected? What quality should this data have (e.g. spatiotemporal quantity, accuracy, reliability, representativeness, etc.)?	What sensors and/or databases can be used to collect the data? What are the data quality requirements for these collection systems (e.g. reliability, granularity, range, scalability, suitability for environment)? What is the lifetime of these sensing technologies?
Physical Layer	What stakeholders are relevant to this layer? What decisions do they make? What competencies do they contribute? What data do they contribute? What is their power on and interest in the DT? What strategy should be used to engage them?	What physical assets need to be considered in the DT system? What processes need to be considered in the DT system? What people need to be considered in the DT system? What environmental factors need to be considered in the DT system? What characteristics of these assets/ processes/people/environmental factors are relevant for the function of the DT? What hierarchical structure can represent this data and their characteristics for the DT?	

The following changes were made compared to the previous versions:

(1) Regarding the physical layer, it was found during the case study implementation that the characteristics of the assets considered can be relevant to the DT and its functionality. Consequently, the DTEA was adapted by adding a *relevant characteristics* element to the physical layer. This element will be represented in the descriptive DTEA by adding the question: *What characteristics of these assets/processes/ people/environmental factors are relevant for the function of the DT?*. As these characteristics also need to be part of the hierarchical structure, the last question was adjusted to: *What hierarchical structure can represent this data and their characteristics for the DT?*.

(2) Next, the feedback was only connecting back to the physical layer, however, in the case study it was shown that a DT can also have a feedback loop to e.g. the modelling layer by adapting and improving the model rather than the physical asset itself. Thus, potential connections from the feedback layer to the modelling layer.

(3) Next, in the evaluation it was recommended that the stakeholders were analyzed more closely than the current framework intends. In the evaluation, it was suggested to combine the current stakeholder assessment with a stakeholder analysis to devise a strategy for the treatment of each stakeholder. Further, it was found that stakeholders with major impact on the results were not identified due to the focus on the impact of the DT on the stakeholders, not the power of the stakeholders over the DT. Thus, it will be suggested to include a common stakeholder analysis technique (Oguz, 2022) known as the power/interest grid in the assessment of the stakeholders. This technique is used to identify and prioritize stakeholders, and create strategies for their engagement in a project (Oguz, 2022). Based on this approach, the following questions are added to the stakeholder elements of the framework: *What is their power on and interest in the DT? What strategy should be used to engage them?.*

(4) Lastly, the lack of consideration of the value provided to the company was addressed in the evaluation. Thus, the service layer was adapted to address the value or benefits of implementing the DT by adding the following question to the data element of the user sub-layer: *What is the value of the recommendations/information to the user?*. However, while it would be useful to answer the question for the stakeholders, other literature has not yet introduced a method to identify or assess the perceived benefits (Bertoni, 2022; Jones et al., 2020). Further, it is difficult to prove the benefits due to a lack of practical examples of implemented DTs (Çetin et al., 2022).

While these four changes address several findings made in the case study and the evaluation, most findings of the evaluation were addressed. However, the aspect of creating a more detailed DTEA for the operational level was not solved. This aspect will be addressed further in the discussion in Section 10.2.2.

9.2 Revised Process for Deriving Strategic Recommendations

In Figure 11, the process of developing recommendations based on the DTEA is shown. During the process of implementing this process, it was found that an iterative process is necessary, as decisions might arise that require the stakeholder to be included in the decision-making. Thus, it was decided to adapt the process to include an iterative decision-making process, as shown in Figure 42.

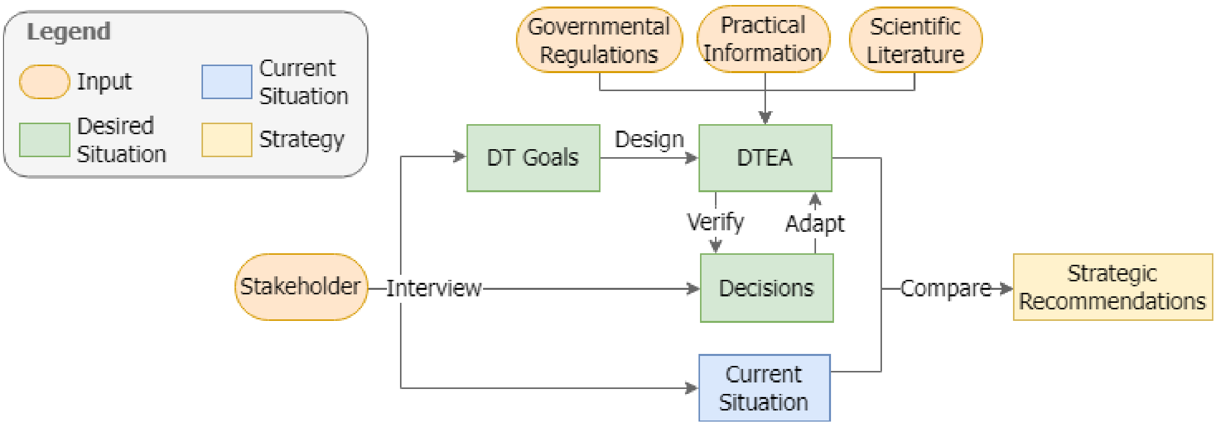


Figure 42: Revised Gap Analysis Process for the Development of Strategic Recommendations

10 Discussion and Conclusion

This chapter will answer the main research question, and then discuss the results and limitations of the research. Lastly, it suggests future research directions.

10.1 Answering the Research Question

This study aimed to answer the research question formulated in Section 1.3:

> *What DT applications can support GWH in environmentally sustainable decision-making processes related to their sustainability goals, and how can strategic recommendations for the implementation of these applications be developed?*

In order to answer this research question, the four sub-questions were answered in the conclusions of Chapters 4,5,6, and 7. These answers are used to answer the research question in this section. The answer will first focus on the first aspect of the research question related to DT applications, and then on the aspect of deriving recommendations.

This study found, that to aid with sustainable decision-making in a company, the DT applications needed to be directed at their priorities regarding sustainability. Consequently, it determined GWHs sustainability goals, which related to the reduction of their CO_2 emissions and the improvement of their building's circularity. Further, this study determined their interests and processes to fit the DT applications to their business structure, which was deemed necessary for companies to be interested in implementing sustainability measures. Based on the sustainability goals, interests, and processes of GWH, nine potential DT uses that could aid GWH with sustainable decision-making were identified (Table 7). These potential DT uses are (1) building energy benchmarking, (2) automated multi-parameter design optimization, (3) automated sustainability rating scheme, (4) BIM-based LCA, (5) BIM-based BCA, (6) automatic material passport generation, (7) calibrated building energy simulation, (8) assembly equipment energy management, and (9) sustainable indoor environmental quality optimization.

Regarding the second part of the research question, the research gap found that there was not enough guidance for the development of DTs in practice, and the problem statement showed that they were interested in knowing what is needed for the implementation. Thus, this research wanted to create an overview of the necessary elements and recommendations for their implementation. To find the necessary elements this study developed a context-specific framework that is directed at identifying the elements of a DT for a specific application, the DT Element Architecture (Figure 9), and formulated questions to guide the definition of these elements (Table 4). Additionally, this study defined a gap analysis process to derive recommendations from the DT Element Architecture (Figure 11). To validate this framework for the intended purpose, a case study was conducted, applying the framework to two of the potential DT uses. The potential DT uses were evaluated by GWH to assess their suitability for the case study, based on the results (1) building energy benchmarking and (4) BIM-based LCA were chosen. The case study developed the DT structure (Figure 30 and Figure 37) and recommendations (Figure 33, Figure 34, Figure 38, and Figure 39) for each DT use. Based on the results of the case study, the framework was evaluated and found to be able to fulfill the purpose of its design. However, the evaluation also revealed several improvements to the framework, which were shown in Figure 41 and Table 21. Consequently, this research concludes that the designed framework was able to develop recommendations for the implementation of a DT in a company.

10.2 Discussion of the Results

Next to the answers to the research questions, this research had other unexpected findings that will be discussed in this section. These findings relate to the guidance included in the framework, the importance of interdisciplinarity to the DT design and implementation, the value creation of DTs, the importance of stakeholders in the framework, and the factors that influence the selection of DT uses. As these were not previously highlighted in this capacity in other scientific literature, they are discussed more specifically in this section.

10.2.1 Framework Guidance

In the research, several different frameworks for DTs have been reviewed. From the four element architecture by Grieves (2015) or the more complex six layer architecture by Pottachola et al. (2022), most frameworks focused more on the definition of the general aspects, and only offered little information on the contents of each layer. The created DTEA with its descriptive counterpart offers a more detailed DT framework, with descriptions of what topics to consider for each element of the DT. The case study showed that it successfully provided an overview of the different elements of a DT and could provide valuable insight for the implementation planning. Through the questions in the descriptive DTEA, it also enables the framework to be applied with little additional research by the user. Consequently, the developed framework offers a more guided approach to the development of DTs.

10.2.2 Interdisciplinarity

The results of the case study showed that while the recommendations given could lead them towards the implementation planning, more detailed information was necessary to proceed in the implementation. When reflecting on the information required to provide this LoD, it was found to be difficult to gather based on a singular viewpoint. Mainly, the addition of specific domain knowledge was thought to be necessary to give these detailed recommendations. This agrees with the findings in literature, where the interdisciplinarity is seen as fundamental to solving the practical problems of implementing technologies in construction (Kockmann, 2019; Wahbeh et al., 2020). Mihai et al. (2022) expands on this and finds that the interdisciplinarity and versatility of DTs is one of the main challenges for implementing it. This aspect reflects the findings in this research, the implementation of a DT could benefit from interdisciplinary cooperation in planning the DT.

10.2.3 Value Creation Through DTs

During the evaluation, it became clear that while the company found that the recommendations could help them implement the DT itself, they were uncertain about the interpretation and the possibilities for value creation within the company. The framework solely focused on the integration in the company based on their goals and processes, and then expects the company to find a way of using the results. However, other research has identified that an inadequate understanding of the benefits to be gained is a major challenge to the implementation of DTs and needs to be further developed (Bertoni, 2022; Jones et al., 2020). Especially, the inability of quantifying the benefits was seen as detrimental, when considering the effort needed to implement a DT (Jones et al., 2020). In this topic, the measurement of the value provided by DTs, methods to discover unknown values, the relation of value to sustainability aspects, and the integration of value into the decision-making through the DT are suggested for further research (Bertoni, 2022). This aspect of DTs was also researched by Barth et al. (2023), who developed a framework to integrate the DT model and value creation aspects. These results imply that integration of value creation into the DT development process should be considered to improve the discovery of the benefits of DTs and their communication to companies, thus supporting DT implementation in practice.

10.2.4 Importance of Stakeholders

When reviewing literature on the implementation of DTs, it was found that stakeholders were considered important to the creation of DTs, yet often overlooked in scientific research (Zhang et al., 2022). Consequently, the DTEA integrates the stakeholders as an integral component in each layer, that enables the considerations of their needs and interests, data ownership, and the possibility of contributing skills and knowledge. This importance was found in literature regarding DT implementation and was confirmed through the evaluation of the framework with a modular construction company. They also suggested expanding the stakeholder consideration from their role in the structure of the DT to a more in-depth planning for their treatment during the development. As stakeholders are often disregarded for DT development, there is a need to investigate these aspects specifically (Liyanage et al., 2022; Merkle et al., 2020). It was found that the analysis of stakeholders for a DT can help with the development and maintenance of the DT system (Liyanage et al., 2022), and help with the integration of stakeholders and their interests in the DT (Liyanage et al., 2022; Merkle et al., 2020). Thus, the integration of stakeholders into a planning framework for DTs might improve the focus on them in the development process.

10.2.5 Influences on DT Use Selection

The DT uses selection was solely based on company internal factors, such as their sustainability goals, development goals, and processes. However, the case study results indicated that external factors are also of importance for companies when considering what sustainability-related DTs might be suitable for them and what value they can provide. Two important factors mentioned in the DT uses evaluation were the governmental policies, and the client understanding. These factors were previously found to be enablers for the implementation of sustainable practices in construction, with both policy structures and stakeholder awareness being recognized (Adams et al., 2017; Hussain et al., 2023). This suggests that these enablers for sustainability are also relevant for enabling sustainability-related DT uses. This could be important for governmental aims to increase sustainability practices in construction supported through digital technologies, such as the 'Emission-free construction' program launched by the BTIC.

10.3 Limitations

The following limitations were identified regarding this study:

1. *Generalizability* – A major limitation of this study is the generalizability. On the one hand, this is due to the case study-based nature of the research, which indicates that the results only apply to the instance that was being studied and cannot be generalized (Johannesson & Perjons, 2021). As this study focused on the implementation of DTs into a small modular construction company, it is reasonable to think it will apply to companies in the same field with a similar structure. However, the applicability of the framework and process applied for companies of a different size, specialization, or fields would need to be assessed first. On the other hand, the DTEA was tested for two sustainability-related DT uses, however, the application for other DT uses in different domains is not yet proven.
2. *Size of the case study* – The case study was conducted with the input of one modular construction company and a limited number of stakeholders within the company. Conducting the study in different circumstances with different stakeholders might yield different results and reveal different viewpoints.
3. *Scalability* – The framework was tested for the use on a singular DT use at a time to fulfil the expectations of a singular stakeholder. The applicability to plan for DTs that aim to combine

several DT uses and consider the requirements of more stakeholders has to be considered in the future.

4. *Completeness of the framework* – The results showed that new aspects to be considered in the DTEA were identified through the application of the framework. As of yet, this application has only been conducted for a theoretical result. It is unclear what additional information might be necessary for the actual implementation of the designed DT.

10.4 Recommendations for Future Research

This research has uncovered several research gaps regarding the field of DT research, the recommendations for future research are:

1. *Maintenance of DTs* – Research on the maintenance aspects of a DT have showed that there was little information on the content and tasks of the maintenance layer, and that the scientific literature was unable to provide a clear picture of its tasks. Despite the lack of specific information, the literature review highlighted that it is an important aspect of the DT lifecycle and needs to be considered when trying to implement a long-term DT in the construction industry. Thus, it is recommended to investigate the maintenance process and its planning for a DT further.
2. *DT implementation using the developed framework* – While the DTEA and the recommendations aim to guide the implementation of a DT, the recommendations given have not yet been applied in practice. To verify the use of the recommendations not only on a theoretical basis, researching their use for the practical implementation, and deriving conclusions about their possible benefits and lacking information could improve the framework.
3. *Interdisciplinary DT design* – This study discussed that there was a need for a more detailed overview and recommendations to facilitate a practical implementation of the DT in a company. It was also concluded that this might require an interdisciplinary approach to developing the design. However, what disciplines are required for different DT uses, and how this interdisciplinary cooperation could be conducted to plan an integrated DT system is yet to be determined.
4. *Value of DT uses* – Similarly, the value of the DT implementation and possibilities for using its results were considered to need a more in-depth planning. Finding ways to identify and quantify the value of a DT for a company before the implementation might play a large role in increasing their implementation in practice.

10.5 Conclusion

This research worked to create a framework for the identification of DT elements, and to develop strategic recommendations based on the framework to help a modular construction company with its implementation. To fulfill this aim, it conducted a scientific literature review to create the framework, which was then tested in a case study directed at the development of recommendations for the implementation of DTs aiding in sustainable decision-making. For the validation of this framework a case study was conducted. It considered the sustainability goals, interests, and processes of a modular construction company to identify sustainability-related DT uses to apply the case study to. In summary, it showed that the created framework was able to give an overview of a DT designed for a specific application of the DT, and that the recommendations would be able to help the company in planning its implementation.

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12 Appendix

12.1 Appendix A: DT Uses Framework

Phase	Key Activities	Historical Analysis	Simulate/Mimic	Extract/Monitor	Predict	Orchestrate

12.2 Appendix B: DT Uses Template

X – DT Use Name

General Details	*DT Use Name*	
	DT Use Category	
	Applicable MC Lifecycle Phase(s)	
	Applicable Key Activities	
Description		
Process		
Potential Value	○ Value X ○ Value Z	
Data and Information Needs	○ Data X ○ Data Z	
Software and Hardware Resources	○ Resource X ○ Resource Z	
Important Competencies	○ Competency X ○ Competency Z	
Generic IS Architecture		

12.3 Appendix C: Evaluation of DT Uses Framework – Focus Group Transcript

Evaluation Session DT Uses Framework – Project Coordinator and Director of GWH on 07/11/2022 & 14/11/2022

*The interview was conducted using Microsoft Teams, and each DT Use Template was adapted into a PowerPoint presentation. The interview had three parties, the researcher (**Q**), the director of GWH (A), and the project coordinator (B).*

- Presentation of DT Use Template 'Automated Multi-Parameter Building Optimization' -

A: I think this is one of the most important things, because the most potential failure will be in the engineering phase. Because it has an impact on everything else that is coming after, in terms of the design, but also the production. And I'm wondering, in which software and modelling software you would integrate this into? You would like to have this integrated into our engineering software?

B: Yeah, I found this a little bit difficult, because from the perspective of the data we have, it will be interesting to focus it more on the inner feedback loop. We have some data on how fast our houses heat up. How fast CO2 emissions will rise up. And after, you can use this in your feedback if the space plan of the building right, if the windows are good in the house. But what I found interesting is to use this in a sense of decision making, because sometimes you think: Why did they make these decisions within the space plan? But what I found difficult in this is two things, one is that quite a lot of decision-making in the design phase, especially in the façade of the house is especially made based on the environment of the building. So, especially how the other houses look like, and to integrate that.

A: More aesthetical you mean?

B: Quite aesthetical. And therefore, we also give space to the architect to be quite aesthetical, because the other aesthetic things we smashed out with this concept.

A: Yeah. But also, if you want to have adoption of the concept houses, you need to have some kind of freedom in the design.

B: Yes, that's it. And quite a lot of decisions we make in the space plan have also something to do with the sizes of the modules. So, there are quite big requirements to make the space plan in that way. And so therefore, I think it is interesting to get more of an idea about the decision making, but I think it is most interesting in the feedback loop, if we made the right space plan. But I don't think it will directly be adopted within the design phase.

Q: OK. So, for the feasibility, you would say more moderate or acceptable?

B: Yes, I think more acceptable. Because it will take quite a lot of time and information to also make these parameters. Because how do you decide which meter is important and how to set it.

Q: OK. Then about the value, how high would you say the value is of implementing method like this is?

B: I think it is more acceptable, because it is difficult to change the design in this phase.

A: And what it's in your opinion or expectation then the design phase impact. it's not only the space plan in my view.

B: I understand, but most of the things like CO2 and especially heat up of a house, if you use that as parameters, it has a big impact on how the design and the façade will look like. And will indeed have impact on the production phase, because the more windows are in, the more impact it will have on the production phase. I think all the parameters will not change the design of the house, because there are other parameters, and especially the wishes of the clients, which impact on these phases. And what will be most important is that we say that all the technical parts should be at the front of the houses, especially due to how warm water should go to the kitchen, and the bathroom.

A: But, if you would look at it as having the information of what the optimum is.

B: Yeah.

A: We could then convince our customer that we found the best, most efficient solution in terms of energy efficiency, etcetera. And that they would go into our standard then. And through that you will have less deviation.

B: But I think therefore it is better to use it more in the feedback loop.

A: Yeah, yeah, I agree. But then the impact could also be, that if we have more standard and therefore less deviation, also in terms of energy performance of the house because of the use of less glass or something like that, that's also a benefit in that case.

B: Yes, it is, yes. So therefore, I would focus on using parameters based on the monitoring which we do on the houses, because then you can also give them insight based on what's the difference in the monitoring. So, in the feedback it has the biggest value.

Q: OK. So, we stay at acceptable value?

B: Yes.

Q: And do you think this could have an impact on the sustainability of your designs?

B: Yeah. I think that is quite more moderate. Because then you can also go to more efficient space plans, more efficient facades, more efficient assembly, less material use.

A: Or material waste.

B: Yeah, maybe it is more to high than moderate then.

Q: OK then we will choose high. Then I think we can go on to the second DT use. Thank you for the discussion.

- Presentation DT Use Template 'Energy Benchmarking' -

A: It's not just the building side of it, it's also in terms of what installation for energy you will use. You can use a water pump, but you can also use the infrared heating panels. So, it's also for comparison of what's the optimum in terms of comfort and energy usage. So, it's not just the constructive building analysis. Because in terms of the future, I think the digital twin can help to make the ideal installation for the HOUTbaar Woningen, which we don't know yet. And in Hengelo for example, we have those four different installation setups. So, those kinds of data you could use. In the same building, what's the difference in energy consumption?

Q: Definitely, yeah. So, what do you think about the feasibility of an energy benchmarking system?

B: Two things, although it is simple, it is the most feasible for us. But I think also for the client this is very interesting, because if clients want us to go more to service contracts, so that you go more for rent including energy consumption.

A: Yeah, but by clients you then mean the end user?

B: No, not the end user. The housing corporation, or a company like Koopmans. Because within TBI we also thought about how to start up a housing corporation like this. And if they want to go more to the service contracts, in that you rent living and not to rent a house. Therefore, it is also important when you go to other business models to first know, what is the general energy consumption for different types of houses. So therefore, it is important. But what Herman is saying is that we are really interested to see if water consumed, and climate system on ventilation consumed, climate installation on energy consumed, and climate insulation. These are the main three types how you can heat up the house. This is very interesting, and therefore, I think the feasibility is also high, because we have most of the data. Especially, we know how much energy each type of systems costs and we also know the differences in temperature and CO2. The only thing is, that we need people to analyze it. These are available, but we need to start with that.

Q: I think that technically you could also automate the process a lot, once you have a structure for analysis.

A: That's true. But then again, somebody needs to do something with the outcome.

Q: What do you think the value would be?

B: That's interesting, because we have an indirect value with this. So, it will not directly give value to geWOONhout, but give better advice to our clients with less energy consumption. It will indirectly have impact on geWOONhout, as the client is interested in our advice and interested in our systems. And we have a reliable system for the future.

A: Yeah. But that's why I also think it's a benefit for geWOONhout, because it can mean that we no longer use a particular system setup, because we know it costs too much and it's less energy efficient, or we have a lot of complaints from customers about the comfort of the of the system. So I think it could give some benefits directly for geWOONhout as well.

B: Yes. So, I think then high.

A: I agree.

Q: Great. And what do you think the improvements to the sustainability off the buildings could be?

B: Also, high.

- Presentation DT Use Template 'Automated Sustainability Rating'-

A: Do we use that currently Linda? Within Koopmans?

B: No.

A: So, it's not a commercial value.

B: No, it is a commercial value. And also, if this is used more in the whole construction industry, the commercial value will also be higher. But we have fought about in 2020. About how to rate. What we wanted to do within Koopmans, is to rate each project on sustainability. But we didn't come that far with it. But what we were interested in, was which type of sustainability and where do you want to wait on? But it is very interesting in a commercial value. Especially when it's coming automatically.

A: Yeah. And the more that it will be one of the criteria in tenders that we need to enter, and it's to be expected with the type of clients that we have, like the housing companies and also the pension funds, will put more points for these kinds of criteria.

B: Yeah, what we thought of before, and I know that they also do that in different types of tenders, is that besides and the concrete structures they deliver, they also always present a wood possibility, if it is possible within HOUTbaarHuis. And they also compare it a little bit, but if the clients want to go further with that that, then it's cost more time and money. But I know for some projects, especially for the municipality or if the clients ask for circularity, that they also deliver a wood project. And I know that, they have the idea that for all projects they wanted to do a sustainability rating for each tender. With some ideas to improve the sustainability rating for the tender.

A: But if I should look at it, it's more like a benefit for Koopmans, than a benefit for geWOONhout in these terms. Because we don't sell.

B: No, it's more that we can get more projects out of it when wooden modules are asked for, but it is especially a benefit for Koopmans.

A: What do you expect in terms of regulations? Because last week we had the outcome of the *Raad van State* in terms of nitrogen. In in terms of that it could create massive opportunities for companies who are able to build in a sustainable way.

B: Yes, but I know where Beccy is coming from, because we already prepared this meeting. I think it is better to go more further to the CO2 emissions for that.

Q: Yeah. I know you talked already a bit about the possible benefits of it. So, how feasible do you think that would be for you to implement?

B: I think that there's a difference between two things. If you think about using this your tender, because then it is important to use it as a difference compared to our competitors. Then it is really difficult to implement it in the current process, because you need a very high quality of information. At the moment, we don't have this information in the tender. So, then I would say it is even low.

A: Unless that you use it based on the standard of the concept houses. Then say based on the standard you have this.

B: That makes indeed a difference. But if you use it for the standard, I think the most impact in this will also come from the façade. Then you have to look for a quick few and then use it. I think then it will be more to an acceptable. If you use this in more the feedback, so checking during the stages what impacts on sustainability different types of space plans, but also different types of materials will have. I think the feasibility will be moderate, because then you can use your standards, then you can look use different type of materials you put in. And then it is easier to use it for your process, especially within geWOONhout go to more sustainable decision making. It would go to moderate. Using it intenders it will be a little more difficult.

Q: OK. Then we will go for moderate? OK. What do you think the value would be to the company?

B: I think it is high, because then you can also have a tool for your decision making.

A: I agree.

B: Maybe you also have to change some of the parameters in it, to make it a little bit more specific also to your waste and other things to incorporate that.

Q: Yeah. OK. And what do you think is the impact on sustainability?

B: Yeah, high.

Q: OK.

- Presentation DT Use Template 'BIM-based Life Cycle Assessment' -

B: I want to add something in this. Also based on the last one about the automated sustainability rating. Compared to the automatic sustainability rating, will the sustainability improvements be higher for this one than for the sustainability rating. So, maybe go more to moderate for that, and this one is high. Because, especially clients, Koopmans, and the governments, are willing to steer more on the LCA than other types of sustainability ratings, which are not based on highly scientific data. And the LCA is also part of the NEN norms, so part of the European Norms for the construction industry. So therefore, I think the impact of the LCA will be bigger. And also, this is for Herman to know, in the LCA you take into account especially the CO2 emissions. I think, based on what is coming now in the construction industry, but also having spoken about it with Andre and Hans, that there will be a CO2 emissions part in taxes. Therefore, it is important to know already in this stage, what the CO2 emissions are going to do with our modules and transports and also the demolition phase. Therefore, I think this is a very important thing, especially also to start with LCAs within our own modules, which are standards. Especially to know what is the CO2 level of it and where can we have impact on that. I feel this BIM-based LCA, when you use the plugin, and I know that there are some plugins available, could support us within our process especially in the product development. When you use the BIM plugin, and in the design phase you change some materials, you directly get feedback on the impact. Therefore, that is more interesting than separate Excel sheets because we have very high-quality modules, the impact of the plug-in will be very interesting. So, I think also for the feasibility, it is quite high.

Q: Yeah.

A: And I'd also think that in terms of our clients to understand, they better understand and know how to interpret the life cycle assessment, instead of the BREEAM and all those other standards.

B: Yes.

Q: OK. So, we have the feasibility and the sustainability. What would you say is the value of having such an assessment?

B: I think it is high. Especially when the construction industry is asked to do an LCA. Then you have also very good comparison with the concrete houses. So therefore, it is very interesting.

A: Yeah, so potentially it's high, because it's also based on what the regulations will be in the in the near future. But in terms of the outcome of the *Raad van State* last week. It's very expectable that those kinds of regulations will follow fast.

B: Yeah, really fast.

A: Yeah, I think so. Because otherwise it will be the solution for being able to execute projects on places where it currently is impossible.

Q: OK, great.

- Presentation DT Use Template 'BIM-based Building Circularity Assessment -

A: Is this something that Sebastian is already working on Linda?

B: Yeah, Sebastian is doing it together with Alba Concepts and other concepts as the building circularity indicator. And they're doing that based on an Excel file sheet. It is that they take out of the module the amount of materials, then put that in their own Excel sheet and then they get the circularity level, which they use now in the markets.

A: Yeah, OK. So, this is what you have to automate.

B: Yeah. Sebastian is now more doing it. That is currently used for the MPG. But you can also do that in the same way on the circularity assessment, but then with other parameters.

A: Yeah, because I know that Sebastian also talked to Peter Palmen about definitions in the IFC model to take up material.

B: Yeah, then you can do it directly because they have to use the NLSfB, but Sustainer is not always working with the NLSfB.

A: I think it's an absolute requirement to have this automated. Because it's going to be a drama to do that on a project base.

B: Yes, I think it is moderate for the feasibility, when it is based on Excel, but it is high when it is a plug-in.

A: Yeah, I would use it as an absolute requirement.

Q: OK, I would say we put it at moderate for now then, because the one that I know exists is based on an Excel sheet, so I cannot promise that it gets more automated than that. What do you think is the value of having such an assessment?

B: Yeah, that's a little difficult. In the market, we are looking for this, but we are not steered by the market to go for a specific type of circularity assessment. And there's also the difficulty that the government doesn't have a norm for calculating your circularity. So, everyone is doing it another way, and most are using Alba concepts, the BCI. Once our competitors also use it, you can compare. But if there's no norm, you can't compare it and therefore the value is not really high. I think the value is more acceptable. It's more to steer on the market.

A: Yeah, it's more a nice to have.

B: We have the circularity numbers of different ways of how to assemble the buildings, but we don't use it because there is no norm.

Q: OK. And what do you think this could do for the sustainability of your projects?

B: If we use it, we can take more out of it. But I think we need the norm. And then, you also know when the circularity market is also indeed good, and not only feeling if it is good.

A: That's why I think that the lifecycle assessment is a is a better way to approach it.

Q: So, then we go for acceptable?

B: Yeah.

- Presentation DT Use Template 'Digital Material Passport' -

A: Is it already a regulation, Linda?

B: No, but it is regulations within the *MIA Vamil* subsidy. There it is regulated that we have to make material passports. But that's also, I think, done by the government to get it regulated, but they now start to use it. Also, to get the software that's accelerated to make it. And within the government there are currently no rules about how the digital material passport has to look like. That makes it also sometimes very difficult. There's a really big difference between all the material passports of different projects. And in the *MIA Vamil* subsidy, I have some problems with that material passport, because it is only encountering what material and the amount of that material in that project. But it is not looking that this is some beam and that gets its own material passport, and that is the plate and gets its own material passport. So therefore, you know at the end of the life cycle of the building how much of its materials there are and how to recycle it, but not how to reuse it. So that is the difference in it. Therefore, I think the value for us in a digital material passport, which is a plug-in; because it is for us very important not to use it in Excel but use the IC data in it; then for us the value is very high in our process. Now they are doing it by hand, and by another company making that material passport, specifically for the subsidized programs. I also think that most of the clients will ask for a material passport. But hopefully, the quality of the material passports will also be higher. However, the sustainability improvement of this type of materials passport is very low, because it is not cooperative on a circularity level or an LCA level. You have then the materials in the passport form, but it is not just pushing us to also improve the sustainability. It only helps the sustainability after its lifespan and during the maintenance phase. But based on how the quality of the material passports based on the amount of materials is now looking like, it also won't help with sustainable decision-making. Therefore, I should say acceptable. And the feasibility in it, you have to have a plug-in, and then it is high. But if it is by an Excel sheet, it is moderate or maybe even acceptable.

Q: Well, the version that I have presented would be directly implemented in the BIM model or IFC file.

B: Then it is high because it is only pushing in. The only thing is that it talks with the same language . If the IFC is also putting it out with the character in it, that character has to be the same in the IFC, and the LCA, and the circularity assessment, and in the material passport. Therefore, we use the NLSfB codes, so that you have the same characters to talk about.

- Presentation DT Use Template 'Calibrated Building Energy Simulation' -

Q: What do you think of how feasible, valuable and sustainable this use is?

B: Maybe Herman, you can help with that. I already have difficulties with the difference between the energy benchmarking and the building energy consumption.

A: I had the same question because for me it would be the same. Where is it different from the earlier energy consumption? I don't see the added value to have this one as well. Because the building in this case is also the house, so the entity is the same.

Q: Yes, the difference is that the energy benchmarking, it's about creating a number at the end. It's basically about analysing data, while calibrated building energy simulations are about predicting the future. And of course, you can use energy benchmarks to come to this solution.

Basically, the energy benchmark would be the input. So, you could create the energy benchmark from the data analysis, and then you compare it with the simulation to get a specific conclusion from it. It is a focus on the performance of the simulation, while the benchmarks give more of an indication if the data is as we expect it. It's kind of a shift in perspective. The one is looking backwards, and this is looking forwards.

B: But then I think the feasibility of this one is more complex, because you also have to think about the future. The parameters will be different. And you also have to do more about scenario thinking in this, the other one is just putting the data in. So, I think the feasibility of this is a little more difficult, because we don't have that many people who are interested and focused on scenario thinking and which can help in performance predictions.

A: No, I agree. Basically, what we do is sell standard housing if it's just a regular house or it's an apartment complex. And I think that if you have more one-off engineering projects, then this could be of more use. At least that's how I look at it.

B: For this second one, I say for the feasibility it will be acceptable, for the value it is also more acceptable, and for sustainability improvements it should be moderate, because you can do something in the future with it.

- Presentation DT Uses Template 'Assembly Equipment Energy Management' –

B: Yeah. I'm little bit doubting, if it's interesting in the sense of how much energy do we use during production, because we only assemble. Yes, we have a crane lane. To have example from the construction industry there you have a crane that picks up the whole day all elements. And for us it is that we have a crane lane, and you turn around a module, then make it in and then put it on each other. We don't have that much movements and the only thing that we do is screwing. When you have more, when you start with the CNC cutting, then it is more interesting, I think. Because then you use a lot of energy, and you also have lots of impacts on how you mill, how you CNC, your elements. So as an assembly factory, I don't know if the energy consumption during production is that much, if it's interesting to follow. Something else which is related to emissions is that maybe it's very interesting to know the amount of waste which is generated during production. We don't make that much waste because most of the materials are already produced and we only assemble. But still during that we make the inner walls, when we are doing the façade, when we are working on the installation materials, still some waste is produced. And waste is also a type of emission. And that should be really interesting to see what places in our production process is there some emission by waste generated.

Q: And emission just in the sense of knowing how much is wasted, or also in optimizing it?

A: I think both. But first to start to know what your waste level is. And then it can help make decisions how to improve that. And I was looking at it also in terms of emissions, not as much energy usage.

Q: Okay. So how feasible would you say is it to implement?

B: I think it is quite feasible, because we know exactly on what type of workstation we are doing what and with what materials. And we also know exactly how much materials we need. So, within the process I think it is quite feasible.

A: Can we then also determine how much we have used?

B: That's maybe what the waste is, you can determine how much is used, you know, what was needed and in between that, there is something which is generated.

A: Yeah. But do we always have the right information to determine the actual usage?

B: That's quite difficult because I don't know if the model is that correct currently. As we have also spoken about the air tightness and also the screws are sometimes a problem when they are not right in the model. And the same you also see with insulation materials. Insulation materials are now quite based on how it fits within the model. But how it fits in the model is that also correct with how you order it from your supplier. Because what we are now doing is cutting it by ourselves. And with the cut you generate waste.

A: The question then is, can you bring the waste down if this is the way the supplier supplies it? If it's now in a certain dimension, you already know that there will be waste.

B: Yeah, but on the other side, we are able to, also with the wood we take. For instance, in the wood, we take that much place from all our suppliers, is that we have impact on our suppliers. That they generate now, for us specifically, a type of material which is in the roofs, which is not available on the market. And it is also made in precisely the dimensions we have spoken with them about. So, the same you can also start to do. We have quite a big impact already on our suppliers.

A: Yeah, I agree. It's true. Yeah. It's also a matter of starting the discussion with the suppliers.

B: Yeah. Because if you have the data, you can start also the discussion, because then you also know where the waste is specifically. Also, with the place as we don't know with Van Hulst how they order it, we also don't know how much waste is being generated.

Q: Okay. So, on a feasibility scale, then would you say is rather high, moderate or acceptable?

B: I think it is more moderate because it is still quite difficult. It fits in the process, but we have to do quite a lot for that.

A: Yeah, I agree.

Q: And how valuable would you say is the implementation to you as a company?

B: I think fairly high, because less waste is also less money to waste.

A: Yeah. It's to direct impact on your cost.

Q: And then what do you think would the impact on the sustainability be, would that be high, moderate or acceptable?

B: It's high, because there also the emissions will be reduced.

Q: Yeah. That's great.

A: Just question on this one. Are the construction emissions also being calculated during the construction on site or only in our manufacturing facility.

Q: Oh, I think you can do both. It really depends on how you scope it. That is totally dependent on what you apply it to. So, if you say, we only want the emissions and the energy use in our production hall or production line, then you would only apply sensors to those machines. Then you would only measure the consumption of those machines and only optimize those. But you can also say, we want to also optimize the use on site and then also apply sensors to those. It just depends on what scope you want to apply.

A: Okay.

- Presentation DT Use Template 'Sustainable Indoor Environmental Quality Optimization' -

B: I found that very interesting, because that this is specifically where we are now working on with the monitoring. We are now doing the monitoring on one side, but this is the idea behind the whole fail-safe trial with TBI where we are aiming to work to. We started now with the less difficult parts for the data and information needs. So, the user preferences and the comfort levels is what we are now working on. So what we now are doing is we installed tablets and they now only see the sensor data on it, but they can also put smiles on if they are happy. And what we now are working on, with *Bizomate*, is that we are now looking for a way that when they put on a smiley, we get information on what they are happy or not happy about. And they get a question back and then we can ask further on it. Are you not happy on this, this, this or this? So that we get more information about the user preferences and comfort levels. So, we are now currently developing how to get the user preferences and comfort level questions in, and how to put that on the tablets. That company is then making a software program to get it on that tablet. And we also can relate that comfort level and preferences, it comes as real time data in our systems, and we can relate it to the levels from the sensors in the monitoring, and we can compare it together. If they are not happy about this, then I can compare it to the information which is coming from the sensors, and maybe I see also a trigger is going off, because the level is too high or too low. So, then we can also compare it. The weather forecast is very interesting because we can get the weather forecast on it, because all the data in the Blockbax environment is now coming from the KNMI, which is the Dutch climate system general.

A: They make the weather forecast.

B: We can also get a weather forecast.

A: One question, Linda. Why is it a different company and not all being integrated into Cloudgarden? Because I know that the basic of the system can do all that and use artificial intelligence also to control the climate systems within the house.

B: That is a private interesting question, but I think therefore we better have an appointment with Jeroen, why it's coming and why it is done in that way. Because I think that's more politics or more other types of choices made within TBI which I don't know.

A: Okay, but that's why I want to have the meeting with the Cloudgarden, separate from TBI.

B: Yeah, just to get an idea of what can Cloudgarden do for us. Yeah, I agree. And that maybe helps us with putting less time in. Just that they say, I need that and they can make it.

A: Yeah, I agree. And, and also if there is already an integrated solution, then why use other suppliers.

B: Yeah.

A: And then we can also inform Hans Schmidt that this is a solution that you can use also in a commercial point of view.

B: Yeah. So, most of the things are already available. The difficulty in it is for this current situation is that we don't have a data analyst and a project manager to bring it together. And what you also need in these types of things is that you have an installation and MEP company working together. Because you give information to the installation, how it should work. So you have to put off that software or you break into that software, and you make changes in that software that it runs on the environment where you have the monitoring, and your comfort levels and preferences in. And it seems very easy to do that, but it is really complex. And when you have problems and the system is not working, then you need an installation plumber to fix that thing. And therefore, we also don't do that now. We have tried it within TBI Woonlab with the HOUTbaar Loft. They tried that, because there are no people living in the house. If there's some problem, you don't have a problem with the people. So you got to look out to go for that, so that you can also put it in houses and solve problems in it. That's makes also feasibility issues.

A: Yeah I agree. And that's requiring a sort of a three-party agreement. Within Koopmans, the installation party and the monitoring party. The system of Cloudgarden is already capable of communicating with all the different protocols which are used for the, the climate systems.

B: Yeah. It's already possible but to get it together, that's the most difficult part of this.

A: And servicing.

B: Yeah. But I think all the other types of digital twins also ask for some actions to get there. And this is not one of the digital twins that asks for more action than the other types of digital twins. We are already quite far at this.

A: Yeah, I agree. The solution is within reach.

B: Yes.

Q: Okay. So based on your considerations, what would you say is the feasibility of actually implementing this?

B: I'm also looking at how we rate the other things. I think that this quite high, technically seen we all are there. We only have to talk with all the parties.

A: I see the problem not in the technical side but in the organizational side.

B: Yeah.

A: And the contractual side.

B: I think it's quite high.

Q: Also with the recent arguments that have been made?

B: Yeah. But it's also for when you go to another digital twin solution like energy benchmarking or BIM-based LCA, we say that was also a high feasibility. But for them we also have to do something in our organization to get people to know what they have to do and to learn about that. So, I think that's both the same.

A: Yeah, I agree.

Q: And what would you say about the value that this measure would present to the company?

A: Well, in my opinion, high. It's not only a technical solution or environmental, but also a commercial opportunity to get a unique selling point on the concept houses of HOUTbaar Woning.

B: Yeah.

Q: And how would you rate this on the sustainability improvements that it could bring to your project?

B: It is always depending on the people who are living in the house, how much sustainability you can get from it and how easy it is to use. And how more it is a self-learning system, then the sustainability will also be higher. Because what is interesting is what we are looking for about this indoor environmental quality, is this that we asked the people who are living in the house when they are most of the time available and when they are leaving. You can do it this way and then you can ask the climate system to run the ventilation capacity a little higher when they start coming home. So, the ventilation capacity is already working. Then will help the sustainability, but it helps even more when you also make it a self-learning system. That they know more specifically when they are exactly coming back, based on what the sensors have measures before. But therefore it needs a more automatic, self-learning software system. So it is always more about how detailed the system itself is and how self-learning, and also about what type of people are living in it. Some are not curious about energy consumption. It always depends. And other have asked us for the monitoring system, because they are fairly enthusiastic about it, and they will use it very well This is depending on the people how sustainable it is.

A: But you can still say that by using artificial intelligence it, it will improve. Also, the emissions side of it, even if the energy request is high. Then it will still be more optimal than by just a manual controlled system. Basically, what will happen is, 'oh, it's a warm, I will turn it off, oh, now it's cold, I'll turn it on'. And then it goes from maximum to zero to maximum to zero. And that's a very inefficient way of energy use. And if you have artificial intelligence, it knows when you want to have the optimal temperature, but it will also take into account that it will not decrease the system if it knows that there will be a demand within a certain period again. So, in general speaking, you can still say that it will improve emissions by using artificial intelligence. Basically, the system will need to be a complete standalone system without any human interference. By just saying 'I like this, I don't like this', that the system will learn what the optimum will be.

B: I think that it is also high. Right?

A: Yeah.

Q: Okay, then we have different systems that you have rated to have a high feasibility, a high value and a high sustainability improvement. We have three systems, let me check, the first one was the energy benchmarking, then the second one was a BIM-based life cycle assessment, and the third one is the sustainable indoor environmental quality optimization Now we need to discuss about which of these methods should be prioritized in the further research. We should rank them in their priority to further develop, so this goes towards the amount of further effort you would want to put into it for now. So, which or what would you say you would prefer to further develop?

A: My idea did that is that the last one that we discussed is already being worked out.

B: Yeah.

A: So perhaps we can choose one of the other to which Beccy can then focus on.

B: Yeah, because also taking in mind that Irfan asked me today to also go further with our sensors, he wants to make a demo for that. About that energy benchmarking and the sustainability and indoor environmental quality. I am really interested in how to get further with digital twins with the LCA, because this directly impacts decision making in in our product model. And the others are already focussed on, but we don't do anything in the LCA. And with the nitrogen and CO2 emissions problems will come soon. I think it will be really interesting to see how we can use our digital twin models to get automatically an LCA.

A: Yeah, I agree. And I was also talking to Sebastian about how to incorporate all the data needs for MIA subsidiaries etc., and therefore this could help.

B: Yeah, I think so.

Q: Then order of priorities is first to focus on the BIM-based LCA, then energy benchmarking and the third priority would be to look into the sustainable indoor environmental quality optimization.

B: Yeah, right.

A: I agree.

12.4 Appendix D: Descriptive DTEA Energy Benchmarking

Layer		**Stakeholders**	**Data**	**Technology**
Service Layer	Users	MEP engineers and installation company Clients	Identify information need of different users	Pre-programmed interface to display data needs
Service Layer	Process	Data analysts → no data analysts available	Interpretation of benchmarking scores	Technology to interpret the data
Service Layer	Feedback	MEP engineers	Decision-making to improve the design ➔ What decisions? ➔ How are they conducted? Passive DT → feedback through human	No technology identified
Data Analysis/ Knowledge Engine Layer		Data Analyst → no data analyst available, nor any experience, possibility of externalizing this process	Energy Benchmarking Method: ➔ Compute EPI values for each entity ➔ EPI recommended as the total (monthly/hourly) energy consumption in (measured energy unit) per (house/installation(s)) ➔ Benchmarking model: artificial neural network, connect to noisy factors Determine benchmark type ➔ Comparing the installations in Hengelo → peer-performance benchmark, benchmark is the best performing house/installation ➔ Comparing the products to their predicted energy use → intended-performance benchmark, benchmark is the predicted performance per product type, need for performance prediction data Compare to obtain benchmarking score ➔ Divide the benchmark by the EPI of each entity	Software to conduct benchmarking methods → not available Access to preprocessed data from storage → recommend cloud computing to integrate TBI server as data storage
Data Storage & Digital Model/ Information Layer		Technical processing skills to transform and pre-process data (or program automatic transformation and pre-processing) → no internal resources, probably external	Transform data points into right format for data analysis → determine what format is needed Differentiation of data points for seasons and day/night cycle → hourly and monthly aggregation period Connect to other data points and/or physical assets Static data → see physical layer Dynamic data → see data acquisition layer	Data Storage → data storage available, should be able to meet future capacity Pre-processing → little pre-processing currently

Data Transmission Layer	Data security → managed by TBI and Cloudgarden, wish for more information at GWH KPN → Provide the SIM-card and internet connection Cloudgarden, TBI →Program the API and the transmission system		Connection from the sensors to a router with a KPN SIM-card to provide internet connection Data is sent to Cloudgarden server Accessibility for TBI through an API
Data Acquisition Layer	Data ownership → TBI owns the data Sensors → Produced by Cloudgarden, but bought and maintained by GWH, little maintenance expected	Electricity consumption data → available on the house and installations level Noisy factors data: ➔ Inside Temperature, CO_2 concentration in indoor air, indoor humidity - available as time series data from sensor ➔ Outside Temperature - Available through database ➔ Thermostat Settings - Can be read out from the thermostat Verify what noisy factors need to be included → energy model All measurements available on a sub-hourly basis.	Sensors for temperature, humidity and air quality → already installed Smart meters for electricity consumption → already installed
Physical Layer	Inhabitants → contractual agreement to monitoring in their rental contract, obligation to inform them of their data fulfilled Owners → contractual agreement to monitoring for 5 years in their purchase contract	• House o Heating ▪ Type of Heating System ▪ Sensor Electricity Consumption o Ventilation ▪ Type of Ventilation System ▪ Sensor Electricity Consumption o Building Characteristics ▪ Product Type o Sensors & Communication ▪ Smart Meter connected to the house ▪ Sensors connected to the house	

12.5Appendix E: Descriptive DTEA BIM-Based LCA

Layer		Stakeholders	Data	Technology
Service Layer	Users	Clients - Overview of different options Product developer - Detailed data about material impact - Make decisions and give feedback based on model results	Presentation/Dashboard - Recommended to use visualizations provided by LCA software - Dashboard with results, quick overview - Results separated by building layer - Detailed results for material selection by GWH product developer Three visualizations: - Comparative visualization of different designs - Visualization of results for internal decision-making - Visualization for clients	OneClick - Option to visualize results in 3D model - What dashboards can be made? - If visualizations are not as intended, the results can be downloaded and integrated into other visualization programs
	Process	Software provider - Allow options to compare and examine data in different levels of detail GWH → define and plan scenarios Engineers → interpret results and compare the designs	Interpretation of Results - Create benchmarks → benchmarking procedure? - Compare different materials - Relate difference in impact to difference in cost → cost of different designs? Download and store results as Excel files Comparative Scenarios - Plug-in/web application enables comparative scenarios to be shown - Standardized scenarios per product - Possible scenarios: CO_2 neutral, bio-based materials, or circular	OneClick LCA - Comparison of different designs possible
	Feedback	Product developer - Make decisions and implement them in the model	Implementation of decisions in the BIM model - Product developer makes decisions on materials Passive DT, requires human intervention and interpretation	BIM Software
Data Analysis/ Knowledge Engine Layer		NMD → set regulations for the software providers, validate the software Software provider → maintain licenses	Life Cycle Impact Assessment - Import quantities from BIM model - Automated Matching of EPDs - Assessment of impacts according to guidelines of NMD - Unit → defined by the MPG as €/m2/yr	OneClick LCA - Software plug-in, performs the calculation - Connected to NMD Cloud-based computing

	(Possibly LCA expert for validation)		
Data Storage & Digital Model/ Information Layer	Engineers/Modelers - Not currently available - Could be external, or create new capacity, should be determined what the possibilities are Software Owner → One Click LCA - Maintain interoperability between BIM and LCA software	Dynamic Data - EPD data - Waste emissions data Static Data - Structural elements and objects - Building service life and GFA Data Models → BIM model currently available - needs to include the data shown in the physical layer → currently not all data included - needs to be kept up to date - LOD 300+ - use NLsfb standards Pre-processing of Data - Life cycle inventory analysis - Need for quantities to be linked to EPDs (classification) → use EPD numbers for matching Data Storage - Storage of data in BIM models → BIM models stored in BIM 360 - EPDs stored in the NMD - Personalized BIM library - Store GFA, building service life, and waste emissions data	BIM Software - Recommended to use Autodesk Revit - BIM 360 for storage OneClick LCA → import data from the BIM model and match it to the EPDs
Data Transmission Layer	Software provider - Needs to maintain access to the database	Updates of the database need to be communicated → automatic in One Click LCA Waste Data → manual insertion into the LCA software Transmission frequency dependent on assessment frequency	Data needs to be accessed through software → One Click LCA
Data Acquisition Layer	Companies - create and maintain EPDs - Urge suppliers to create EPDs - choose suppliers for EPD availability NMD	Environmental Impact Data → from database (NMD) - EPDs need to be in accordance with NEN-EN15804 - Category 1 EPDs are preferred - Identify EPD number Waste Data → amount of waste produced available, data collection scheme implemented	No specific technology required.

	- Collect EPDs and verify them		

Physical Layer	Engineers/
	Architects → need to have specific data ready
	
	Purchasers → need to define what suppliers will deliver the materials
		House and <u>all</u> included objects:
		- Structural elements and objects
		    o Material quantities (volume or quantity), max. ±3.5%, include hollow spaces
		    o Supplier
		    o Material name → non-generic
		    o IFC classes → use to build hierarchical structure
		- Gross floor area (definition in documentation) → calculate for each module based on floor plans
		- Calculation period → building service life is defined by GWH as 50 yrs, ensure compliance with guidelines	

12.6 Appendix F: Informed Arguments for Building Energy Benchmarking Evaluation

ID	Requirement	Informed Argument
1	The DT design enables the comparison of the building performance of different houses and to their predicted performance.	Benchmark types and their application are addressed in the benchmark type considerations, and the data analysis layer.
1.1	The artefact addresses how buildings can be compared to one another.	
1.2	The artefact address how buildings are compared to their predicted performance.	
2	The DT design can distinguish the energy consumption of different installations from the consumption of the whole house.	This aspect is considered in the benchmarking target, and implemented in the data acquisition layer.
3	The DT design enables the performance assessment based on the electricity use.	This aspect is considered in the benchmarking target, and implemented in the data acquisition layer.
4	The DT design enables a temporal differentiation of the performance.	The temporal differentiation is addressed in the energy performance index considerations, and implemented in the data acquisition layer.
4.1	The artefact addresses a seasonal differentiation in the performance assessment.	
4.2	The artefact addresses a day/night differentiation in the performance assessment.	
5	The DT design connects the energy use measurements to measurements of influential factors.	The aspect is considered in the noisy factors considerations, and implemented in the data acquisition layer.
5.1	The artefact connects the indoor CO_2 concentration to the energy performance.	
5.2	The artefact connects the outside temperature to the energy performance.	
5.3	The artefact connects the inside temperature to the energy performance.	
5.4	The artefact connects the thermostat settings to the energy performance.	

12.7 Appendix G: Informed Arguments for BIM-Based LCA Evaluation

ID	Requirement	Informed Argument
1	The DT design provides a highly automated process.	The sub-requirements 1.1-1.4 are fulfilled.
1.1	The assessment is directly derived from the BIM model.	The direct connection is addressed in the data analysis/knowledge engine layer.
1.2	The assessment is conducted through a software plug-in for BIM.	The use of a plug-in function is addressed in the data analysis/knowledge engine layer.
1.3	The artefact automatically connects material EPDs to the material quantities from the BIM model.	The connection between the EPDs and the quantities from the BIM model through direct EPD matching is addressed in the data storage & digital model/information layer.
1.4	The artefact structures the BIM model data in the NLsfb format.	The use and interpretation of the NLsfb format is addressed in the data storage & digital model/information layer.
2	The DT design conforms with national regulations regarding LCAs.	The national regulations of the Netherlands are discussed in Section 8.3.3, and were integrated in the DT design.
3	The DT design uses EPDs from the NMD as input for environmental data. .	The use of EPDs from the NMD is discussed in the data acquisition layer.
4	The planned DT will allow for material level design decisions to be made.	The sub-requirements 4.1-4.2 are fulfilled.
4.1	The artefact enables the user to compare the environmental impacts of different material choices for their design.	The comparison of materials is addressed in the service layer.
4.2	The artefact plans for a high specificity of the LCA results.	The specificity of the results is addressed in Section 8.3.3.3, and in the data acquisition layer.
5	The DT informs the user of updates to the EPDs used in their designs.	The notification scheme of One Click LCA is discussed in the data transmission layer.
6	The DT design provides visualizations for different users.	The sub-requirements 6.1-6.3 are fulfilled.
6.1	The artefact includes a dashboard to visualize the data.	The visualization of the data is addressed in the service layer.
6.2	The dashboard can be used to compare different design choices.	The visualization of the data is addressed in the service layer.
6.3	The artefact can visualize the DT results within the BIM model.	The visualization of the data is addressed in the service layer.
7	The results on a project level will not change after the completion of the project.	The use of a download for Excel option is discussed in the service layer.