P5 Thesis 2022-2024

Navigating Digital Twin Implementation in the Circular Built Environment.

Identifying technological inhibitors to implementation of digital twins from the perspective of early and potential adopters

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Abstract

According to the United Nations the Poles are melting, rising sea temperatures are killing ocean life, the acidity of sea water is rising and on land forests are burning (United Nations, 2019). This together with industrialization, increased urbanization, increased population growth and unsustainable consumption patterns this has put a strain resources (Ari & Yikmaz, 2020). Circular economy models, in contrast to the linear model, dissociate economic growth from the consumption of primary raw resources. Since the construction sector is still in its infancy with a circular economy, there is a very high potential for enhanced resource reuse, higher use of recycled materials, and increased sustainability (Stroetmann & Huttig, 2020).

The main research question is: "What are the observed and anticipated barriers and challenges for early and potential adopters of Digital Twins technologies in the Dutch circular-built environment?"

The hypothesis of this study is that an organization's circularity strategies are influenced by its specific needs, leading to a perceived need for digital replicas with specific functionalities. This decision, influenced by operational and strategic goals like material durability, environmental harm reduction, and resource utilization, influences the choice of digital twin technology. Companies with complex circularity plans may opt for more advanced digital twins, while those with simpler requirements may opt for more flexible solutions.

The research will employ several methodologies to provide a comprehensive view of digital twins' potential in the circular built environment. A literature review was conducted of CE economy strategies within the built environment. The goal was to identify challenges and barriers in the adoption of digital twins as a tool for circular construction. Semi-structured interviews were conducted to identify barriers experienced by those potentially using these technologies and challenges experienced by those implementing them. The literature review was used to set up a framework for conducting these interviews, categorizing actors based on their roles and circular strategy. The final aspect of the research was the solutions sourced from interviewees, categorized and cross-referencing with barriers. This provided an overview of potential solutions to the barriers and challenges identified during the interview's initial stages, ensuring a critical reflection of the solutions provided.

This thesis explores the barriers and challenges faced by early and potential adopters of Digital Twin (DT) technologies in the Dutch circular-built environment, focusing on Circularity Strategies, Digital Twins, and the unique challenges encountered by adopters. Through a comprehensive analysis of the built environment, circularity strategies, and DT archetypes, the study identifies key factors affecting the adoption process, such as financial constraints, technological hesitancy, data ownership, and regulatory issues. Interviews with early adopters revealed both common challenges, such as standardization and financial limitations, and specific solutions, including leadership in communication, modular technologies, and collaboration with research institutes. Potential adopters, on the other hand, reported additional barriers like technological immaturity and lack of clear business models. The study's findings emphasize the need for continuous technological improvements, the development of financial incentives, and stronger regulatory frameworks. Despite progress in addressing some challenges, significant barriers, such as data privacy and ownership, remain unresolved. The study concludes by offering recommendations for future research and strategies to support broader adoption of DTs, emphasizing collaboration, phased implementation, and a flexible approach to categorizing digital twin practices in the circular-built environment.

Key words: Digital Twins, Digital twin archetypes Barriers, Challenges, Circular Economy, Circular Construction

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1.0 Introduction

According to the United Nations the Poles are melting, rising sea temperatures are killing ocean life, the acidity of sea water is rising and on land forests are burning (United Nations, 2019). This together with industrialization, increased urbanization, increased population growth and unsustainable consumption patterns this has put a strain resources (Ari & Yikmaz, 2020).

The construction industry has a large impact on these resources, with 40% of resources being consumed this industry, 40% of global waste being produced by this industry and a third of global emissions being produced by this industry (van Stijn, Gruis, 2019). In Europe the building sector generates up to 9% of the GNP, and studies have shown that 39% of global emissions are generated by this sector and in the EU, it is responsible for 46% of waste generated (Çetin, Gruis, & Straub, 2021). Based on volume, construction, and demolition waste (CDW) is the largest waste stream in the EU (European Commission, 2022). This is also true in the Netherlands, where the building sector generates up to 45% of waste whilst only accounting for 10% of the countries GNP (Luscuere, 2018).

Among all economic activity, the construction industry (CI) has one of the most linear value chains. The sector of architecture, engineering, construction, and owner operators (AECOO) must adopt more circular practices. Reusing construction materials, reducing waste, and using techniques that are more resource efficient are all examples of sustainability as a prominent trend in this industry (European commission, 2018). Recent studies have shown that only 50% of waste in the EU building sector is recycled (The European Union, 2018) and downcycling is a significant issue in this sector (Hossain, Ng, Antwi-Afari, & Amor, 2020). Circular economy models, in contrast to the linear model, dissociate economic growth from the consumption of primary raw resources. Since the construction sector is still in its infancy with a circular economy, there is a very high potential for enhanced resource reuse, higher use of recycled materials, and increased sustainability (Stroetmann & Huttig, 2020).

Circularity in the built environment refers to more than just the components of a building's structure. Along with putting a focus on a social base, it also seeks to combine an economic framework where we are more aware of the wider environment both during and after building. Therefore, using circular economy concepts in the built environment offers developers and building customers a substantial potential to decrease lost value sources, boost the financial return from built environment assets, and facilitate the achievement of sustainability targets (Acharya, Boyd and Finch, 2020).

In research by Çetin, Gruis, & Straub (2022), its stated that Digital technologies are thought to make it possible to apply the circular economy in the built environment. Digitalization is a strategy to increase the sector's productivity, competitiveness, and efficiency. However, digitalization also impacts environmental goals, such as those concerning more eco-friendly solutions, energy efficiency, products recycling, and sustainability certifications. These strategies rely on data, understood as digital, interoperable, incremental and traceable. Data related concepts, such as digital data templates (DDT) and digital building logbooks (DBL), (Mêda, Calvetti, Hjelseth, & Sousa, 2021). Çetin, De Wolf, and Bocken (2021), identify and map ten enabling digital technologies to facilitate a circular economy in the built environment. Namely: (1) additive/robotic manufacturing, (2) artificial intelligence, (3) big data and analytics, (4) blockchain technology, (5) building information modelling, (6) digital platforms/marketplaces, (7) Digital Twins, (8) the geographical information system, (9) material passports/databanks, and (10) the internet of things.

A Digital Twin is not a novel idea. Although it has long been used in digital simulations in fields like manufacturing, aircraft, and the car industry, its use in the built environment is only recently becoming more common (Parmar, Leiponen, & Thomas, 2020). The use of digital models of assets to provide simulations and an information link to a real-world entity (i.e., a physical twin) is one recent interpretation of the "Digital Twin" concept in the built environment research. This opens up opportunities for data-centric decision making in asset operations and management (Brilakis et al., 2020). Furthermore, a Digital Twin describes a concept that connects physical and virtual objects through a data linkage. However, Digital Twins are highly dependent on their individual use case, which leads to a plethora of Digital Twin configurations (van der Valk, Haße, Möller, & Otto, 2021).

As stated by, van der Valk, Haße, Möller, & Otto, (2021), the configuration of digital twins is highly dependent on its use, thus the information collected is dependent on the goal of the digital twin.

Furthermore, data collections are also dependent on this and can vary along variables, namely, form of data acquisition, rate of data acquisition, data sources, data type. Data handling and distribution is another variable along which Digital Twins can vary, namely across, data governance, data link (the flow of information between virtual and physical), interface, interoperability (degree of standardization) and the purpose of a Digital Twin. The last variable along which Digital twins can vary is their conceptual scope. It's based on accuracy (degree of representing reality) and the time of creation(for example before or after the physical asset has been realized) (van der Valk, Haße, Möller, & Otto, 2021). Thus, there is currently no set definition of Digital Twins, and it's based on the individual use case (Cimino, Negri & Fumagalli, 2019)(Wagner, Schleich, Haefner, Kuhnle, Wartzack, & Lanza, (2019).

Numerous technologies and approaches are incorporated into the DT concept. Several systems are used to support the construction process, from design (such as structural dimensioning software), through execution and construction (such as systems for developing and monitoring schedules), to information repositories (such as common data environment (CDE), databases, and information containers) that will be

used in the use phase later (facility or asset management). The goal of a Digital Twin in the built environment sector is to connect physical assets' sensors to cyberspace in order to facilitate data gathering, processing, and analysis for the purpose of simulating and controlling actual assets or constructed objects, (Boje, Guerriero, Kubicki, & Rezgui, 2020).

To simulate performance of assets, Digital Twins, which provide a virtual representation of the real environment, are already widely employed in the industrial, aerospace, and automobile industries. Digital Twins have several applications in the built environment industry, including autonomous decision-making, feedback and control, proactive maintenance, and more. The main benefit of a Digital Twin is its machine learning capabilities, which are supported by the data gathered over the course of the building's existence by sensors as well as by simulations performed on the model. (ARUP, 2019). For Digital Twins to be operational, components from BIM or a custom 3D model of the building, along with also Wireless Sensor Network integration and data analytics, meaning that is a central element that operationalizes other technologies. (Tao, Cheng, Qi, Zhang, Zhang, & Sui, 2017).

Thus, it can be stated that Digital Twins, through connecting different technologies and allowing for data to be operationalized, through AI and algorithms, can promote circularity through not only extending the life of assets, through allowing for circular use of assets, but also by enabling end of life circular strategies (Çetin, De Wolf, & Bocken, 2021).

As stated above digital twins can be a key element in the transition from linear construction to circular construction, through being part of a wider framework of technologies. Some research has been conducted into such possible frameworks. Çetin, Gruis, & Straub (2022), discuss several technologies, including Digital Twins, and how they could interact and help the implementation of circularity strategies. In her Master thesis Jia (2021), designed a possible framework for how digital twin can enable different circular strategies in the built environment. In research by Çetin, Gruis, & Straub (2022), an analysis has been conducted of how Digital Twins have been used by social housing organization to achieve circularity goals. However, there is currently a gap in literature in regard to the barriers and challenges for the adoption of this technology.

1.1 Problem statement

As the paper by Çetin, Gruis, & Straub (2022), shows that the adaptation of Digital Technologies to reach circularity goals is already underway. Using several other technologies, such as drones, material passports and AI different configurations were created and used to implement circular strategies.

However, there is within scientific literature a lack of research regarding the possible barriers and challenges for circular construction in the actual Dutch built environment. Therefore, this research will focus on the current adoption of Digital Twin technology in the Dutch built environment by current adopters of the technology and those who are active in the realization of circular real estate but have not yet implemented the technology. In order to identify challenges experienced with the adoption of the technology, issues with current forms of adoption and possible barriers or challenges observed by those who are yet to adopt the technology.

1.2 Research relevance

According to the European commission (2021) the construction industry in the Netherlands had in 2021 already mostly recovered from the covid-19 pandemic and is continuing to grow. With it being a mayor consumer of raw materials and a significant producer of emission, several authors have expressed the importance of its transition of a linear to a circular economy. Previous research has also highlighted the importance of technological enablers, such a Digital Twin, in the achievement of circularity goals (Antikainen, Uusitalo, & Kivikytö-Reponen, 2018) (Çetin, De Wolf, & Bocken, 2021). The Horizon Europe framework programme aims to advance European capacity in key enabling technologies. Here research & development on digital, industry and space technologies are combined to support a competitive, green, digitized and circular European industry (European Commission, 2022).

The European Union through its horizon project sees the use of Digital Twins and other digital technologies in the built environment as key technologies needed for the realization of its sustainability goals, which includes the realization of a more circular built environment. In addition, these technologies other technologies currently being either directly or indirectly developed are according to the European commission expected to support the implementations of Digital Twins (European Commission, 2022). Digital Logbooks incorporate the information from other technologies such as material passports and also logs events such as change of ownership, tenure or use, maintenance, refurbishment and other interventions over the physical asset's life cycle in a standardized manner. These can be used and shared to create interoperable Digital Twins, which can facilitate several EU initiatives and Strategies, such as the "European Green Deal'' and its Renovation Wave and the new Circular Economy Action Plan (Gómez-Gil, Espinosa-Fernández, & López-Mesa, 2022).

However, there is no research which considers the barriers and challenges for the adoption of these technologies. By making these observed and possible barriers explicit and by offering potential solutions, the adoption of these technologies in the context of the Dutch built environment could potentially be expedited and help realize the goals of the Dutch government for circularity in 2050

(Ministerie van Infrastructuur en Waterstaat, 2021), and in turn the European Union (European Commission, 2022).

2.0 Research question

Research question that will be addressed in this thesis will address the identified gap in research. The main research will be segmented into several sub questions that each address key concepts that need researched to answer the main question.

The **main research question** is: "What are the observed and anticipated barriers and challenges for early and potential adopters of Digital Twins technologies in the Dutch circular-built environment?"

Sub question 1. How is circular construction implemented in the Netherlands?

a. What is the Built environment?
b. How is the construction industry structured?
c. What is circularity in the built environment and how can it be achieved?
d. What are the barriers to the creation of a circular construction industry?

Sub question 2. What are Digital Twins for the Circular Built environment?

a. What are Digital Twins and what are their capabilities?
b. How can they enable circular strategies?
c. How can they been used to enable circular strategies in the Dutch construction sector?

Sub question 3. What are the observed and perceived barriers and challenges for the adoption of Digital Twin in circular construction?

a. Which barriers and challenges did the early adopters of Digital Twin technologies experience?
b. What barriers and challenges do other potential users perceive in the adoption of Digital Twin technologies?

Sub question 4. What are the employed and possible solutions for the experienced challenges and how do these overlap with barriers?

Moreover, this thesis assumes that the strategies for circularity employed by any organization are determined by the needs of the corporation. Consequently, this creates a need or perceived demand for digital replicas with particular functionalities. The **hypothesis** of this thesis states that *the circularity techniques employed by a corporation are determined by its special needs, which subsequently influence the desire or perceived necessity for digital twins with certain characteristics. This in turn dictates the barrier or challenges that are related to the implementation of Digital Twin technologies for circularity purposes*. This indicates that an organization's operational and strategic goals, such as prolonging the durability of materials, minimizing environmental harm, or maximizing resource utilization, have a direct impact on the choice of digital twin technology it selects or desires to employ. As a result, companies that have more intricate, or advanced circularity plans are likely to go for digital twins that have higher accuracy and better integration capabilities. On the other hand, companies with simpler or basic requirements may choose more flexible and uncomplicated digital twin solutions. This hypothesis emphasizes the interconnectedness between a company's goals of achieving circularity and the technological needs it requires. It suggests that the adoption of digital twin technology within the circular economy is primarily influenced by the specific and changing demands of the organization's circularity strategy.

Research output

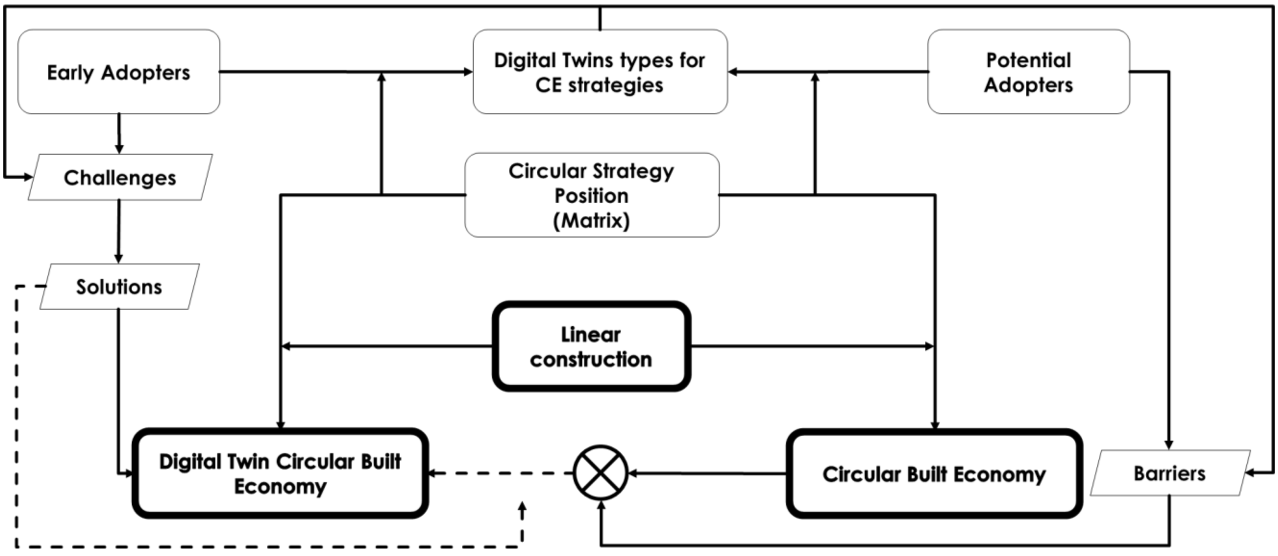
The research output for this paper will be an index of categorized challenges and barriers for the implementation of digital twin as tools for the circular built environment. This will be added to a secondary set of information, possible solutions, gathered through the interviews sessions with the relevant industry experts.

Personal Study targets

The personal study goals for this thesis are to garner knowledge about the role of technology in the transition to a more sustainable built environment. By researching Digital twins, it is possible to get a better understanding of how organizations formulate and align their cooperate goals and the goals related to circularity. This is due to Digital Twins being connected to multiple other technologies.

3.0 Research method

3.1 Conceptual framework



Barriers blocking use of digital twins

- - - - Possible application of solutions to allow for Digital Twin implementation in the CBE

Figure 1: Conceptual Framework

As shown in the conceptual framework and as stated by both the Dutch government (Ministerie van Infrastructuur en Waterstaat, 2021) and the European Union and the European union (European Commission, 2022), there is currently due to environmental issues and resource scarcity a desire amongst governing institutions to transition from a linear construction model to a circular construction model.

As shown in Chapter 1 digital twins are a key asset in the realization of this transition, through their ability to facilitate and or enhance the execution of circular strategies. However, there is a gap as stated there is currently a gap in literature which does not explore the perspective of actors meant to use these technologies. As these concepts in the built environment are relatively new it is important to consider the perspective of current users (early adopters) and similar parties in the circular

construction industry who has not or not yet adopted Digital Twin technologies (Potential

Adopters).

Challenges in this paper are defined as the aspects of the implementation process which were and are experienced as negative by early adopters.

Barriers are the aspects of the implementation process which potential adopters perceive as hinderance to the adopting digital twin technologies. By gathering both the challenges and the barriers and then aggregating solutions employed by early adopters we can potentially increase the use of Digital Twins as a tool for circular construction, thus facilitating the transition strived for by both local and continental government institutions.

The hypothesis underpinning the research as stated above is that circular strategies employed informs the choice for a specific digital twin to support its strategies, which in turn dictates the barriers and or challenges encountered when trying to implement the technologies.

In the context of a company's strategy within the circular built environment, this approach drives the selection of a specific digital twin. The chosen digital twin configuration, in turn, introduces a distinct profile of barriers and challenges. Essentially, the organization's strategic objectives for circularity dictate the type of digital twin that is best suited to support those goals. However, the specific digital twin configuration also brings its own set of challenges, whether they be technical, regulatory, or related to data management, that must be addressed to ensure successful implementation. This cycle highlights the direct influence of a company's circularity strategy on its digital twin adoption and the subsequent hurdles that arise from this choice.

3.2 Research Method

3.2.1 Research Framework

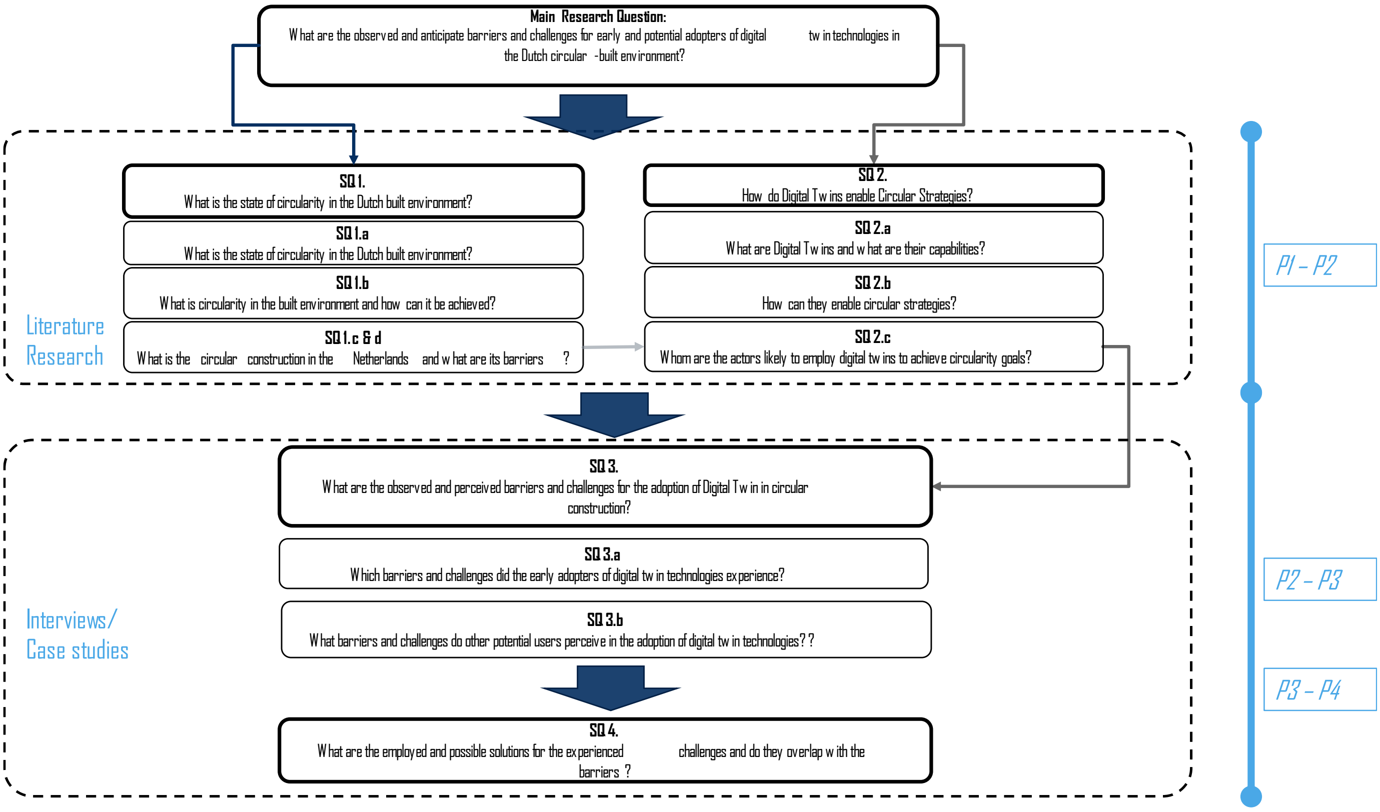


Figure 2: Research Design

As shown in the research design model (Figure 2), several methodologies will be employed during this research. The methodologies answer a specific questions and form a basis for the subsequent methodology employed. This to ensure that the interviews conducted in the third phase are based on a comprehensive view of what digital twins can do in the circular built environment, whilst also taking into account the current reality of how these technologies are used.

Literature study

In support of this research a literature study will be conducted into a variety of subjects. Firstly, a literature review will be conducted of CE economy strategies within the Built Environment, Furthermore, research will be conducted into how Digital Twins can and have been implemented to facilitate the execution of varies circularity goal.

In support of this research a literature study will be conducted into a variety of subjects. Firstly, a literature review will be conducted of CE economy strategies within the Built Environment and the state of circular construction industry in the Netherlands. This will answer the first sub questions and address the relevant aspects of the implementations of digital twins in the Circular Built environment, such as, the implementation the relevant actors as will be supplemented with additional research into these technologies to provide an understanding of the full potential of these technologies.

Furthermore, research will be conducted into what Digital Twins are and how they can and have been implemented to realize circular construction goals. Lastly research will be conducted into the state of the Dutch construction industry and its transition towards a circular economy model instead of a linear one. The goal of this literature research will be the creation of a base for the identification of challenges and barriers in the adoption of Digital Twins as a tool for circular construction.

Semi Structured interviews

This will be supplemented with semi structured interviews. This will be done to identify what barriers experienced by those who already use these technologies and the potential challenges that those who could implement them perceive. This is done in order to get a complete overview of the of both actual and potential obstacles for the implantation of Digital twin in the construction Industry to achieve circularity goals. To conduct this phase of the research the conducted literature review will be used to set up a framework for conducting these semi structured interviews. The framework will include the necessary themes to be addressed and the necessary actors. The data gained for, identified actors in the literature study will be categorized according to their roles and the type of circular strategy they employ. This will answer both sub question 3a and 3b.

As shown in figure 2 the last aspect of the research conducted of this will be the solutions these will be sourced from the interviewees and categorized and cross referenced with barriers. This will and answer sub question 4 and will be conducted will be based on the participants expertise. It will provide an overview of potential solutions to the barriers and challenges that were identified during the interview's initial stages. The early adopters will be asked how they solved Challenges experienced . This will provide an overview of their expert opinion solutions that are feasible based on their use. Furthermore, this process will also require a critical reflection of the solutions provided. This in order to get an opinion that clearly considers both benefits and negatives of potential solutions, and to address whether they are relevant to the digital twin-oriented scope of this thesis.

3.2.2 Data

Data Collection

This research is conducted to identify the potential and possible barriers experienced by actor when implementing Digital Twins to enable circular strategies. Initially a literature review is conducted. This will provide an understanding how the Dutch built environment is structured, its current state, its current progression towards a CE and which actors are relevant. Furthermore, this will also provide and understanding of Digital Twins, how the function and how the can and are implemented to achieve circular construction goals. This literature research will also address why the use of Digital Twins as a tool for implementing circular strategies in the Built Environment is relevant by making clear the potential benefits. By conducting interviews with potential l and actual users this research aims to collect both objective and subjective data. By collecting both the potential and actual barriers (both surpassed and implementation stopping), already implemented solutions can be identified. The use of semi structured interviews allows for the interviewee to provide a broader and a more context full answer to the questions asked. Furthermore, it also allows for potential follow up questions to be asked, it provides them maximum latitude to explore and address unknown issues which may not have been known to the interviewer (Adams, 2015).

Data analysis

The terms and conditions of the procedure, which include the recording, transcription, and publication of the transcriptions, will be indicated in a consent form that will be given to the interviewees prior to the start of any interview. It is crucial that the interviewees sign the consent form and are informed of the purposes for which and how their data will be used. The interview will be conducted, then it will be recorded, transcribed, and subjected to the program for analysis. Additionally, it would be a good idea to write this as soon as possible following the interview in case there were any other comments that was not properly recorded or incomplete. The information will be filtered according to relevance and subject after the interviews have been transcribed by the software. AI will be used in this research ethically, adhering strictly to established guidelines and ensuring full transparency throughout the process. Its primary role will be to assist in highlighting key aspects of interview data, providing clear and unbiased summaries in bullet-point form. All AI-generated content will be carefully checked for accuracy to ensure it reflects the original material without errors or misinterpretations. The AI will not create new content but will strictly summarize existing information, helping the researcher conduct a thorough and reliable analysis for the thesis. Additionally, it will also be used as a paraphrasing tool where necessary. Data privacy and integrity will be maintained at all times.

Data protection

The FAIR data guiding principles by Wilkinson et al (2016) will be applied to assure the security of the data. The acronym FAIR stands for Findable, Accessible, Interoperable, and Reusable data. First, the research must be added to the Delft University of Technology's repository to make sure it can be found. Second, after it has been uploaded, the research can only be accessible via the Delft University of Technology website. Thirdly, the research has been documented in English and the terminology and terms used in it have been well explained to ensure interoperability.

The reference list, which is provided in the references chapter at the end of the report, contains references to all sources that have been mentioned or cited in APA format. The names and any other sensitive information pertaining to the interviewees will also be omitted in order to further safeguard them. The report will only contain the information that has been extracted from the interviews; the transcript will not be included.

3.2.3 Ethical considerations

The study takes into account ethical issues to make sure no harm is done either during or after the dissemination of the research in addition to the FAIR Guiding Principles. First off, because the research entails choosing materials, a decision-making process that involves multiple parties.

The inquiry emphasizes the "human aspect" heavily. To identify potential barriers and challenges to the use of Digital twins for circularity in the Built environment its necessary to rely on human perspectives. These are either based on experience or on perceptions. It should be emphasized that this could make people cautious when providing their own version of the "objective truth" in order to look better, which might result in skewed information. This calls for careful planning for how to approach interviewers with particular queries. Second, participation in the study is fully voluntary, and interviewees are free to decline any further participation. This means that the study has no mandatory questions. Finally, when performing the studies, consideration will be given to three ethical factors: anonymity, privacy, and informed consent. The interviewee's privacy will therefore be protected throughout the investigations. During the interviews, the participants' privacy must be protected. It is asked of the participants if they consent to being recorded.

Once the thesis study is over, these recordings are destroyed. Both online and offline data will be securely stored. The responses provided by the respondents will be made less traceable in order to meet these ethical concerns and ensure that they do not face any consequences as a result of the publication of their thoughts and opinions. This will be accomplished by leaving out their names and merely listing their organizational positions and professions. Each interviewee will also receive consent forms informing them that they will be recorded. After the research is over, the recordings will be destroyed, but the information obtained from the interviews will be safely stored in an online database. The interviews can only be carried out when the interviewees have been informed of the statements in the consent form and have provided their consent.

4.0 Literature Research

4.1 The Built Environment

4.1.1 Definition

According to Hassler and Kolher (2014), the concept of the Built Environment (BE) is a relatively recent one. Bartuka (2007) states that the built environment is comprised of four characteristics, namely:

- All humans made, organized and maintained structures
- Made to fulfil human needs, goals, and principles
- Made to shelter humans from the environment
- Impacts the natural and built environment whilst also influencing human interaction with the environment

In this thesis this definition of the concept will be used as it provides a holistic overview of the built environment which also takes into account the impact on the natural environment. As this study also concerns the circular economy it is a fitting definition, because both Bartuka's (2007) definition and the circular economy concept address ecological and environmental factors.

Batruska (2007), further breaks down the concept of the built environment into several interconnected components. In the research conducted he states that the built environment consists of Products (materials and commodities for enhanced task specific performance), Interiors (a selection of specific products in a defined space for the facilitation and insulate activities), Structures (an organized cluster of spaces defined by and constructed with products), Landscapes (exterior natural – and built environments), Cities (clusters of structures and landscapes of varying sizes), Regions (clusters of cities and landscapes of varying sizes grouped together based on aligned sociological, economic, political and or environmental factors. The last components Batruska (2007) mentions is the Earth which contains all other components.

As this study focuses on the implementation of Circular Economy and the use of Digital Twins the components regions and the earth will be left out of consideration when discussing the built environment as this falls outside the research scope. Furthermore, as this paper also focusses on the implementation by actors who are either private or not wholly government institutions the components of cities are not a primary aspect of this paper. If field research however indicates that there is an effort on municipal levels to employ digital twins as tools for the circular built environment this will be addressed.

An examination of the literature reveals that it is still difficult to achieve a shared understanding of the built environment (Moffatt & Kohler, 2008). The literature includes a wide range of references to the built environment, often focusing on buildings but occasionally mentioning other types of infrastructure like bridges and dams (Gibberd, 2015; Ness & Xing, 2017). While some consider the built environment as all human-made surroundings that serve as a backdrop for human activity (Batty, 2012; Hillier, 2008), others see it as a collection of abstract places or as a socio-ecological system (Moffatt & Kohler, 2008).

In all sectors of the Built Environment there are several stakeholders involved with the realization of the built environment. Traditionally, stakeholders are “groups or individuals who can affect or are affected by an issue” (Schiller, Winters, Hanson & Ashe, 2013).

In a thesis by Koukopoulou, (2020) a literature study conducted Identified several stakeholder groups in the circular built environment. namely Owners and planners, the Design and Built Team, Suppliers and Manufactures and Recovery Specialists.

The first group owners and planners could consist of developers, real estate investors, financiers, owners, users and facilities managers. This group sees the realized building as an asset either to generate revenue or to provide functionality and are depending on the duration of their interaction with the building either focused on the short- or long-term lifecycle of the building.

The second group consists of Architects, Designers Engineers, Consultants (Allied Professionals), and Contractors. Their duties include the eventual construction of the building project as well as the planning, design, calculation, and review of the building's construction in line with a predetermined budget and architectural standards.

Suppliers and Manufactures can be divided into, Suppliers Vendors Manufacturers, Distributors and Installation companies. They oversee the supply of products, components and the provision of services. They are also in charge of managing these supplies ensuring that both quantity and quality meet the set standards. The specific role of installation companies the provision, installation, and maintenance of specific components, through multiple life cycle stages.

The Deconstruction Companies, which are in charge of demolishing buildings and separating waste flows of limited value, the Demolition Companies, which disassemble buildings while preserving the value of their individual components to enable reuse, and the Waste Management Companies, which are in charge of recycling waste for energy recovery or landfill disposal, are the recovery specialists.

This thesis focuses on the Dutch built environment, which is the result of the building industry. In 2007, the Dutch construction sector experienced an economic downturn due to the housing market crisis. Since then, output in the sector has grown at a faster pace than the average across Europe, and in 2018 construction saw the strongest production growth of all industries. The industry has recovered from the crisis, and the second quarter of 2019 saw an increase in GDP to 9489.46 EUR Million from 9178.06 EUR Million in the first quarter of 2019. One of the positive aspects of the crisis was that a number of initiatives were formulated to boost the industry, such as the concept of the 'Circular Economy'.

Thus, it can be stated that the Dutch government has taken various steps to support the construction and infrastructure industries during the COVID-19 pandemic, including the launch of financial aid schemes for small and medium-sized enterprises (SMEs) and the creation of a construction industry task force to identify short-term projects. Despite the challenges of skilled labour shortages and late payments, the government has continued to invest in infrastructure and transport projects. The digitalization of administrative activities has been widely adopted by Dutch SMEs, and the Netherlands is recognized as one of the top innovators in the world. While the Dutch economy is predicted to recover after a 3.7% decline in GDP in 2020, the construction sector is expected to face challenges in the short term but experience growth in the long term.

4.1.2 Linear built environment Phases

Phases and sub sectors

In this chapter we will quickly review the different phases in the creation of the built environment and the actors in these phases. This is necessary to create insight in whom interviews are conducted with and to create an understanding of the activities they could possibly undertake within the process or life cycle of structures in the built environment. In research conducted by Hurlimann, March, Warren-Myers, Nielsen, Moosavi, & Bush (2022) a literature review was conducted to identify key sectors of the built environment, the key phases in the life cycle and the actors in these phases. The four key sectors identified by Hürlimann et. al, (2022) were the Urban Planning, Property, Construction and Design. Based on these identified sectors the phases of the of the built environment life cycle were identified in conjunction with the key actors this was based on other literature sources. This was then adapted into the table below. This will as stated above be adapted into tools for analysing the built environment.

According to the research by Hürlimann, et. al, (2022), the built environment can be sub divided into 4 key sectors. Namely Urban Planning, Property, Construction and Design.

The define these sectors as follows:

Urban planning: Urban and regional planners create and implement land use plans and advise on economic, environmental, and social concerns.

Property: Real property is land, and anything linked to it, therefore the Property Sector covers many areas of the built environment. Property actors own, develop, build, invest, value, sell, lease, manage, direct and indirect invest, and manage the built environment where people live, work, shop, and play.

Construction: "The construction, destruction, renovation, maintenance, or repair of buildings and infrastructure" is the construction sector.

Design: The built environment design sector has three subsectors: Urban design "concerns the arrangement, appearance, and function of our suburbs, towns, and cities." It creates places where people live, interact, and interact with their surroundings. Landscape architects "use natural sciences, environmental legislation, and planning policy to develop spaces that improve amenity, add beauty, support the environment and economy, and increase social health and welfare." "Architecture" entails planning, designing, and sketching buildings. Architects advise builders and negotiate building contracts.

To this was added by Hürlimann, et. al, (2022), an overview of relevant actors and activities as shown in the table below.

Phase	Activities	Key Stakeholders
Change Initiation	- Setting the scene (political & policy triggers) - Consideration of socio-economic trends (population, mobility, economic growth) - Hazard and risk assessments (e.g., sea level rise, relocation needs)	- Urban Planners - Allied Professionals - Engineers
Strategic Planning	- Research and analysis - Development of planning tools (zoning, regulations, design guidelines) - Infrastructure planning - Consultation with experts, community, and elected representatives	- Urban Planners - Allied Professionals - Urban Designers - Engineers - Landscape Engineers - Construction Managers - Owners/Investors
Project Initiation/Consideration	- Initiation of specific projects by public and private sectors - High-level conceptual design - Development and financial feasibility assessments (ownership, viability, market conditions)	- Urban Planners - Property Advisors - Property Developers - Owners/Investors - Allied Professionals - Architects - Urban Designers - Landscape Engineers
Design	- Development and iteration of designs - Design review and community consultation - Detailed design and construction documentation	- Architects - Urban Designers - Landscape Engineers - Urban Planners - Property Advisors - Property Developers - Allied Professionals

Phase	Activities	Key Stakeholders
Costing and Approval	- Detailed costing and quantity surveying - Planning and statutory approvals - Financial and legal support for acquisitions - Revisiting construction documentation	- Property Developers - Engineers - Construction Managers - Allied Professionals - Property Advisors - Urban Planners - Architects - Urban Designers
Construction	- Production of the built form as planned - Construction of infrastructure - Handover of components to private owners/public entities - Landscape establishment	- Construction Managers - Landscape Engineers - Property Developers - Property Managers - Allied Professionals - Owners/Investors
Use and Ongoing Management	- Continual strategic planning to meet population needs - Maintenance, repair, and renovation of built environment components	- Owners/Investors - Urban Planners - Urban Designers - Landscape Engineers - Allied Professionals - Property Managers
Renewal, Recovery, Decommission	- Identification of future trends and renewal needs - Planning for renewal, recovery, or decommissioning - Recovery of reusable components before decommissioning - Restarting the process	- Urban Planners - Property Managers - Property Developers - Property Advisors - Allied Professionals - Engineers

Table 1: Phases, activities and key stakeholders in the built environment (adapted from Hürlimann, et. al, 2022)

In conclusion, the concept of the Built Environment (BE) is relatively new and includes all human-made structures that are designed to fulfil human needs and shelter humans from the environment. The BE also impacts both the natural and built environment while influencing human interaction with the environment. The BE can be broken down into several components, including products, interiors, structures, landscapes, cities, regions, and the earth. This study focuses on the circular economy and the use of digital twins, and the components of cities, regions, and the earth are left out of consideration. The key sectors of the built environment are urban planning, property, construction, and design, with each sector having various stakeholders involved in realizing the built environment. The stakeholder groups in the circular built environment include owners and planners, the design and built team, suppliers and manufacturers, and recovery specialists.

4.2 Circularity

4.2.1. Circularity definition

The built environment, which includes buildings, infrastructure, and urban spaces, has a significant impact on the environment and society. The construction and operation of buildings and infrastructure consume significant amounts of resources and energy and produce large amounts of waste and emissions. To address these challenges, there is increasing interest in the concept of circularity in the built environment. Circular economy principles offer a new approach to resource management that focuses on reducing waste, reusing materials, and promoting sustainable design and construction practices. This literature review aims to provide an overview of the definitions and key concepts related to circularity in the built environment, as well as the challenges and opportunities associated with its implementation.

Circular economy is an economic system that aims to keep resources in use for as long as possible, extract maximum value from them while in use, and recover and regenerate products and materials at the end of their life (Geissdoerfer, Savaget, Bocken, & Hultink, 2017).

Circularity in the built environment involves several key concepts, including resource efficiency, waste reduction, reuse and recycling, and the creation of closed-loop systems. Resource efficiency refers to the optimization of resource use in the design and construction of buildings and infrastructure. This includes the use of sustainable materials, the reduction of energy consumption, and the optimization of water use. Waste reduction involves the minimization of waste and the promotion of waste reduction practices throughout the building's lifecycle. Reuse and recycling involve the recovery of materials from waste streams and their use in new products or applications. Closed-loop systems involve the creation of systems where waste is eliminated or reused, and resources are continuously cycled back into the system (Geissdoerfer et al., 2017).

	Definition of Circularity	Source
1	The use of closed-loop systems, efficient building design, and the reduction of environmental impacts through the use of circular design principles.	Ellen MacArthur Foundation (2019); Geng et al. (2013)
2	A model of development that aims to create a regenerative built environment, in which resources are restored and natural systems are replenished.	Lieder & Rashid (2016)
3	A process of designing and constructing buildings and infrastructure that aims to maximize the use of renewable resources, minimize waste and emissions, and create a positive impact on the environment and society.	Hu et al. (2018); Geissdoerfer et al. (2017)
4	A model of development that seeks to create a closed-loop system in which waste is minimized, resources are used efficiently, and natural systems are preserved and enhanced.	Lieder & Rashid (2016)
5	A process of designing and constructing buildings and infrastructure that prioritizes the use of renewable energy sources and aims to reduce the environmental impact of building operations.	Geissdoerfer et al. (2017)
6	A concept that emphasizes the need to design buildings and infrastructure with the entire life cycle in mind, including the extraction of raw materials, production, use, and end-of-life management.	Benachio, et al. (2020)
7	A strategy that aims to create a closed loop system in which waste is minimized, resources are used efficiently, and the environment is protected through the promotion of sustainable practices.	Joensuu, et al. (2020)
8	A shift from a linear economic model of "take-make-dispose" to a circular economic model of "reduce, reuse, recycle".	Geyer, R., Jambeck, J. R., & Law, K. L. (2017)
9	An approach that aims to retain as much value as possible from resources, by designing for disassembly, reuse, and recycling, in order to minimize waste and reduce the environmental impacts of the built environment.	Munaro, M. R., Tavares, S. F., & Bragança, L. (2020
10	A model that promotes the transformation of the traditional linear economy into a more regenerative and restorative system, by focusing on the design and development of closed-loop material cycles and promoting the reuse of resources.	Korhonen, J., Honkasalo, A., & Seppälä, J. (2018).
11	A regenerative system that uses renewable resources, designs for disassembly, and reduces waste, in order to maintain the value of materials and create sustainable environments.	Liu, L., & Wu, G. (2020)
12	A model that promotes the design of regenerative systems in the built environment, by reducing waste and promoting the reuse and recycling of resources, in order to create a more sustainable and resilient system.	Bocken, N. M., et al. (2014)
13	A model that promotes the development of closed-loop material cycles, through designing for disassembly, reuse, and recycling, in order to minimize waste and create a more sustainable built environment.	Ghisellini, P., Cialani, C., & Ulgiati, S. (2016)
14	An economic model that aims to create a closed-loop system of resource use in the built environment, through promoting design for disassembly, reuse, and recycling, in order to minimize waste and optimize resource use.	Geissdoerfer, M., et al. (2017)

Table 2: definitions of circularity based on various sources

Circularity in the built environment is a multifaceted concept that has been approached from various perspectives. To provide a comprehensive understanding of circularity, a review of peer-reviewed academic literature was conducted, and 14 definitions were identified (Table 2). These definitions highlight the different aspects of circularity, including the reduction of waste, the use of renewable resources, the extension of product lifespan, and the integration of systems thinking.

Liu and Wu (2020) define circular economy in the built environment as an approach that aims to reduce waste and optimize resource use through the redesign of processes and systems.

Bocken et al. (2014) identify different sustainable business model archetypes that enable circularity in the built environment, including closed-loop, value recovery, and product-service systems. Bocken et al. (2018) argue that circular economy represents a paradigm shift towards a more sustainable and regenerative economic system that fosters innovation and resource efficiency. Ghisellini, Cialani, and Ulgiati (2016) provide a comprehensive review of circular economy and its expected transition towards a balanced interplay of environmental and economic systems.

Geissdoerfer et al. (2017) propose a sustainability paradigm shift towards circular economy, emphasizing the importance of regenerative systems, closed loops, and system-level interventions.

These definitions provide a framework for understanding circularity in the built environment and highlight the different aspects that need to be addressed for the transition towards a circular economy. The identification of these definitions enables practitioners and researchers to align their efforts and contribute towards the implementation of circular economy practices in the built environment.

After reviewing the definitions of circularity in the built environment given in the previous four tables, it is possible to group them according to similarity. The following are the groups:

Cluster 1: Closed-loop system and efficient resource use

- The use of closed-loop systems, efficient building design, and the reduction of environmental impacts through the use of circular design principles. (Ellen MacArthur Foundation, 2019; Geng et al., 2013)
- A model of development that aims to create a regenerative built environment, in which resources are restored and natural systems are replenished. (Lieder & Rashid, 2016)
- A model of development that seeks to create a closed-loop system in which waste is minimized, resources are used efficiently, and natural systems are preserved and enhanced. (Lieder & Rashid, 2016)
- A strategy that aims to create a closed loop system in which waste is minimized, resources are used efficiently, and the environment is protected through the promotion of sustainable practices. (Joensuu et al., 2020)
- A model that promotes the transformation of the traditional linear economy into a more regenerative and restorative system, by focusing on the design and development of closed-loop material cycles and promoting the reuse of resources. (Korhonen et al., 2018)
- An economic model that aims to create a closed-loop system of resource use in the built environment, through promoting design for disassembly, reuse, and recycling, in order to minimize waste and optimize resource use. (Geissdoerfer et al., 2017)

Cluster 2: Renewable resources, waste minimization, and positive environmental impact

- A process of designing and constructing buildings and infrastructure that aims to maximize the use of renewable resources, minimize waste and emissions, and create a positive impact on the environment and society. (Hu et al., 2018; Geissdoerfer et al., 2017)
- A process of designing and constructing buildings and infrastructure that prioritizes the use of renewable energy sources and aims to reduce the environmental impact of building operations. (Geissdoerfer et al., 2017)

- A model that promotes the design of regenerative systems in the built environment, by reducing waste and promoting the reuse and recycling of resources, in order to create a more sustainable and resilient system. (Bocken et al., 2014)
- A regenerative system that uses renewable resources, designs for disassembly, and reduces waste, in order to maintain the value of materials and create sustainable environments. (Liu & Wu, 2020)

Cluster 3: Design for lifecycle, resource retention, and waste minimization

- A concept that emphasizes the need to design buildings and infrastructure with the entire life cycle in mind, including the extraction of raw materials, production, use, and end-of-life management. (Benachio et al., 2020)
- An approach that aims to retain as much value as possible from resources, by designing for disassembly, reuse, and recycling, in order to minimize waste and reduce the environmental impacts of the built environment. (Munaro et al., 2020)
- A model that promotes the development of closed-loop material cycles, through designing for disassembly, reuse, and recycling, in order to minimize waste and create a more sustainable built environment. (Ghisellini et al., 2016)

In summary circularity in the built environment according to this literature review can be defined as a multifaceted and evolving framework that addresses environmental and social issues related to building and infrastructure construction and operation. This will be the definition that this thesis will be based on. The reviewed literature covers circularity, emphasizing closed-loop systems, resource efficiency, waste reduction, and regenerative design. Authors define circularity in different ways, from closed-loop material cycles to renewable resource promotion to the life cycle of buildings and infrastructure. These definition clusters help clarify circularity in terms of closed-loop systems and efficient resource use, renewable resources and positive environmental impact, and design for lifecycle, resource retention, and waste minimization. previous tables all point towards this circular approach, with some emphasizing the importance of a systemic approach, stakeholder engagement, and the use of renewable resources.

4.2.2 Circularity Strategies

In this section we will discuss the circularity strategies available in the Circular Economy. Despite advances, Mannan and Al-Ghamdi (2020) noted that Circular Economy (CE) principles for all building life cycle stages have not been evaluated. Several comprehensive frameworks address circular strategies for specific built environment aspects. Frameworks for building components (Van Stijn & Gruis, 2019), prefabricated buildings (Wood, 2012), industrialized housing construction (Block et al., 2017), new building design and construction (Eberhardt, Birkved, & Birgisdottir, 2020), sustainable building construction (Lopes de Sousa Jabbour, Jabbour, Godinho Filho, & Roubaud, 2018), material and product flows. However, these frameworks often focus on specific life cycle stages, production methods, or resource flows, lacking a holistic view.

According to Bocken et al. (2020) and Bocken, Koumbarakis, Stahel, & Dobrauz-Saldapenna (2021), there are four categories of circularity strategy when considering the mechanisms behind the flow of resources

(Bocken et al. 2016, Bocken et al. 2020). In this section comprehensive approach to categorize circular building strategies under four core CE principles will be addressed: regenerate, narrow, slow, and close resource loops (Bocken, de Pauw, Bakker, & van der Grinten, 2016; Rosa, Sassanelli, Urbinati, Chiaroni, & Terzi, 2019). We also introduce "collaborate" as a strategy to address construction supply chain inefficiencies, which are crucial to the circular built environment (Honic et al., 2020). The following sections explain each principle and circular building strategies in detail. Bocken et al. (2020) added regenerate based on research by others (Hens et al. 2018; Cardoso& Free, 2009; the Ellen MacArthur Foundation 2015; Stahel, 2008). This due to the need to also consider the need for less toxic materials and increase of renewable materials for a circular built economy)

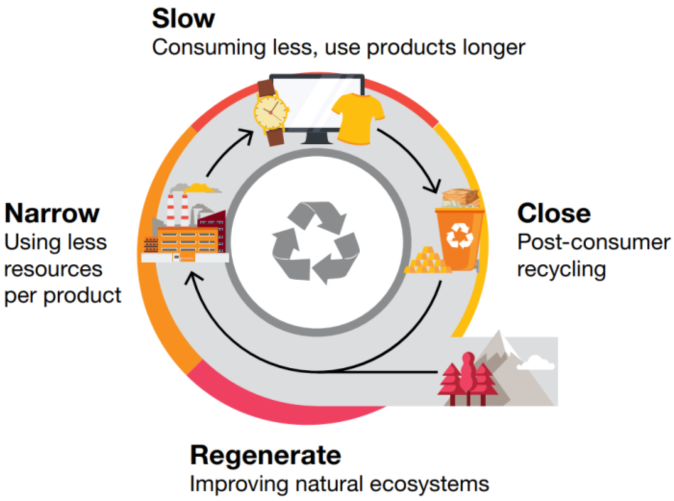


Figure 3: circularity strategies for resources (Bocken, Koumbarakis, Stahel, & Dobrauz-Saldapenna, 2021)

Regeneration

While CE definitions may use "regeneration" and "restoration" interchangeably, their meanings are not adequately addressed (Morseletto, 2020). Repair and remanufacturing bring products back into the economy in technological cycles (Morseletto, 2020), while regeneration improves systems by improving the environment (Bocken et al., 2023). Regenerative design goes beyond green and sustainable building to generate self-sufficient resource flows and initiate place-based co-evolutionary systems between humans and nature (Mang & Reed, 2012). From "doing things to nature" to "being part of nature" (Reed, 2007). The circular BE, which co-creates with local communities and uses sustainable and healthy resources to improve people and ecological systems, relies on regeneration, according to this study.

Regenerating in the context of business refers to practices that sustain natural ecosystem services, use renewable and nontoxic materials, and are powered by renewable energy (Ellen MacArthur Foundation, 2015; McDonough & Braungart, 2002). This strategy aligns with the 'biological cycle' of the circular economy and emphasizes the use of renewable energy in the 'technical cycle' (Hens et al., 2018; Luttropp & Lagerstedt, 2006; Cradle to Cradle Products Innovation Institute, 2019; Vestaron, 2019). For instance, Vestaron has developed biological pesticides that are safe for humans, birds, fish, and pollinators, replacing synthetic pesticides (Ellen MacArthur Foundation, 2018;). Apple is companies using installed solar energy capacity (Lystek, 2019). Another principle of regenerating is to recover nutrients from urban areas, which involves identifying ways to reclaim valuable nutrients typically lost in urban environments. Lystek Inc., for example, helps the city of Guelph convert biosolids from wastewater treatment into organic nutrients for local farms (Ellen MacArthur Foundation, 2018;)

Narrow

Narrower resource flows are resource efficiency and product input reduction, per Morseletto (2020). The circular BE defines ‘narrow' as a building that uses fewer resources over time. Early design decisions impact building performance and operations (Eberhardt et al., 2020). Building system upgrades may reduce water and energy use. The three groups summarize narrowing strategies:

Based on dematerialization (Skillington & Crawford, 2020), this method reduces building and building goods primary resource inputs. Optimizing lightweight structures (Block et al., 2017), using renewable energy in production, designing sanitary hot water circulation systems (Pimentel-Rodrigues & Siva-Afonso, 2019), and assessing their added functions to avoid the second bathroom are examples. Designing with reused materials reduces resource inputs.

Narrowing is a concept that involves using fewer products, components, materials, and energy in design, production, delivery, use, and recovery processes (Baumann, Boons, & Bragd, 2002; Bocken, Allwood, Willey, & King, 2012). One approach to narrowing is designing products with low-impact inputs, such requiring less land, water, and CO2 compared to alternatives (Ellen MacArthur Foundation, 2018; Impossible Foods, 2019). Another approach is incentivizing users to consume less, strategies which incentives less energy and material use (Bocken, Mugge, Bom, & Lemstra, 2018). Additionally, maximizing the use capacity of products through sharing can reduce the overall number of personally owned goods, as seen with the online platform Peerby that enables people to share everyday items (Allwood, 2014; Lacy et al., 2014; Peerby, 2019).

Slow Resource Loops:

Slowing refers to the practice of using products, components, and materials for longer periods of time (Bocken et al., 2016; De los Rios & Charnley, 2017; Mont, 2008; Bakker et al., 2014; Cooper et al., 2014; Luttropp & Lagerstedt, 2006). One principle for slowing is "design for physical durability," which means creating products that degrade more slowly than comparable ones on the market for example through reduced product complexity (Den Hollander et al., 2017). Another principle is "offer the product as a service," where companies provide the desired result rather than selling the physical product (Bocken et al., 2016; Mont, 2008). This approach allows companies to minimize resource intensity over time. An ecosystem principle for slowing is "turn disposables into a reusable service" (Hamans et al., 2018). A Loop involves various stakeholders, including end users, circular economy enablers, retail brands, and external service providers (Aquafil, 2019).

Closing Resource Loops:

Closing refers to the process of bringing post-consumer waste back into the economic cycle (Bocken et al., 2016). One principle for closing is designing products with materials suitable for primary recycling. This could allow waste to be manufactured into new Nylon 6 without any loss of quality (Ellen MacArthur Foundation Case Studies, 2019).

Another principle for closing is enabling and incentivizing product and component returns. This could be done by providing a QR code that generates that enables free return after use, which then leads to credit for the owners next purchase when they send back products (Hopper & Nielsen, 1991).

Organizing local waste-to-product ecosystems is an ecosystem principle for closing. SOOP, for instance, has created an ecosystem where waste (such as coffee grounds and orange peels) is collected from offices, processed into raw materials, and used to produce new products like soap, which are then delivered back to the same offices. This could be through the creation of initiatives where waste is collected and remanufactured into a new product which can be sold or used in new initiatives (Scruggs, 2013).

Overall, these principles and examples demonstrate the various approaches and strategies. The analysis in the appendix contains the worked-out sources that are sourced for the table below which lists the circularity strategies for each of these approaches.

Narrow:	
1	Design with low-impact inputs Design products with 'ingredients and materials that require less land, energy, water and/or materials to produce.
2	Design light-weight products Design products that are lighter than comparable products on the market to reduce energy to transport.
3	Design for multiple functions Design products with multiple functions. Multi-functional products can reduce the overall number of products and may be usable by different user groups.
4	Eliminate production waste Eliminate any type of waste from production processes, for example material scraps or excess heat and electricity. For example, waste and save cost reduction through centralized disposal, Artificial intelligence enabled image recognition software and training based on gathered waste data.
5	5. Enable and incentivize users to consume less Incentivize users to use less energy or material during the use of energy or material-using. The firm HOMIE offers washing machines through a pay-per-wash model. By monitoring user behavior, the company increases the resource efficiency.
6	Organize light-weight urban transport Organize lighter forms of transportation. The lighter the vehicles, the lower the amount of energy and materials required to transport people and goods.
7	Localize supply where appropriate Find more local suppliers, where appropriate. More local suppliers decrease the amount of energy needed to transport goods.
8	Maximize capacity use of products Maximize the degree to which the capacity of a product is used. This is sometimes referred to as 'sharing', where multiple user groups have access to the same product.
Slow:	
1	Design for physical durability Design products that degrade more slowly than comparable products on the market.
2	Design for emotional durability Design products that users will love and trust over a long period of time. This could be done through long term warranty for materials
3	Design for ease of maintenance and repair Design products that can be easily maintained or repaired. Maintaining means inspecting the product to retain its functional capabilities. Repairing is about restoring a product to a sound/good condition after decay or damage.
4	Design for easy dis – and reassembly Design products that can be easily separated and reassembled.

5	Design for upgradability A product is upgradable if its functionality or performance can be improved during or after use.
6	Design for standardization and compatibility Create products, components or interfaces that also fit other products, components or interfaces.
7	Enable users to maintain and repair their products Create services that enable users to care for their product. Through providing access to repair knowledge and an inventory of spare parts.
8	Remanufacture existing products and components Recover value from collected end-of-use products by reusing their components for the manufacturing of products with the same functionality. For example, through collecting and remanufacturing them into as-new certified spare parts.
9	Repurpose existing products and components Take existing products and components and take them out of their context to create new value with them. For example, by adding additional use cases to building components.
10	Provide an unconditional lifetime warranty Offer your customers a life-time warranty, adding a promise to products that are made to last.
11	Encourage efficiency Encourage your customers to moderate the consumption of your products. This by encouraging users to maintain and trade back products once they don't use it anymore.
12	Provide the product as a service Offering the product as a service keeps the ownership with the firm and creates incentives to increase their lifetimes. You can Offer product-, use-, or results-oriented models.
13	Organize maintenance and repair services Make sure that your products can last longer through maintenance and repair services. They can be offered by the manufacturer of a product or by third-party providers
14	Upgrade and adapt existing products A product is upgradable if its functionality or performance can be improved during or after use. Try and integrate upgrading services into your offering.
15	Turn disposables into a reusable service Make use of or provide services that replace disposable with durable products. These disposable parts can be reused by including actors retail brands, service providers (e.g., cleaning and transport service) and end users.
Close:	
1	Design with recycled inputs Design with materials that have been recycled from other products and components. The 'Design for Recycled Content Guide' supports firms in opting for more recycled content in their products.
2	Design components, where appropriate, with one material Composite materials are often hard to recycle because they cannot be separated. Design components, therefore, where appropriate, with only one material to increase recyclability.
3	Design with materials suitable for primary recycling Try and design for primary recycling, that is: recycling that can turn materials into materials with equivalent properties.
4	Design for easy disassembly at the end of the product lives Easy disassembly allows product components to be more easily recycled.
5	Reuse and sell components and materials from discarded products Create new value from wasted products and components.
6	Enable and incentivize product returns Make sure that you can get the products back that you put on the market for example allow owners to scan a QR code or other tracking technology in to facilitate sending back to manufacturers Sending back products earns users credit for their next purchase.
7	Recycle products in proper facilities Make sure that the products you put on the market get recycled in proper facilities. The initiative 'Closing the Loop' supports users and sellers to be material-neutral and waste free. This by facilitating the gathering of materials and components and properly recycling them.
8	Build local waste-to-product loops Create local resource loops by turning the waste of a given facility into new products that can be sold back to the facility. For examples allow for local collection of components or raw materials and provide these to local projects from the same owners or other initiatives
9	Engage in industrial symbiosis Share or exchange by-products, materials, energy, or waste among nearby firms. For example, using by products from other nearby industries, or providing wate material after use to other industries.
Regenerate:	
1	Design with renewable materials Design products with renewable and low-carbon materials. Timber wood, for example, can replace non-renewable building materials. Renewable materials should only be chosen when its extraction rate is equal to or lower than its recovery rate. Further, next to its properties, materials need to be selected based on their expected end-of-life treatment to avoid unintended consequences.

2	Design self-charging products Design products that can charge themselves with renewable energy. This for example through integration of solar cells in different components.
3	Design with living materials Living materials leverages the properties of natural materials. Evocative, for example, produces mycelium-based fibres and materials with natural glue properties.
4	Design with non-toxic materials Avoid using toxic materials and substances in any of your products or operations. Toxic substances tend to accumulate in the biosphere and cause negative health effects for humans and other species.
5	Produce and process with renewable energy Build up your capacity as a company to produce and process with renewable energy.
6	Power transportation with renewable energy Find ways to power your transportation needs for materials for example with renewable energy. Through a light-weight mobility system, powered by renewable energy.
7	Power the use of the product with renewable energy Find ways of powering your product with renewable energy, through creative partnerships or product and service design. Through providing portable devices with photovoltaic panels that can power every-day electronics.
8	Embed renewable energy production in the existing infrastructure Find ways of making renewable energy production part of the existing infrastructure. 'Solar Roadways' has developed a modular system of solar panels that can be walked and driven upon.
9	polluted ecosystems Contribute to regenerating polluted ecosystems that affect your business. The Ocean Cleanup Project develops technology for collecting environmental waste.
10	Manage and sustain critical ecosystem services. Engage in projects that manage and sustain the natural ecosystems that surround and/or affect your business operations

Table 3: Sub strategies adapted from Koumbarakis, Bocken, Stahel, & Dobrauz-Saldapenna, 2021 and

4.2.3 The circularity matrix

A necessary aspect of the interview process is the use of a Circularity Matrix in which it is possible for the interviewees to place the Digital Twin Configurations that will be discussed further on in this paper. This is to identify clarify their definition of a digital twin and its use in relation to possible or perceived barriers. This is necessary as use might also dictate identified barriers and challenges, in relation to use, circularity strategy and actor type. In order to make this matrix, on the Y-axis the four circularity strategies discussed above are placed. These strategies are the slow, narrow, close and regeneration strategies. On the x-axis the Phases for the Built Environment discussed above are Placed. These are, Change initiation, Strategic planning, Design, Costing and approval, Construction, Use and ongoing management, Renewal recovery and decommission. It should be stated that three clear categories of phases are visible here. The pre build phase, the construction phase, The use Phase, and an end of life phase. It should be stated that the end of life phase should not be considered the end of life for the materials but rather a built asset. Combining these factors results in the following matrix below. Furthermore, in the matrix for each of the strategies the following strategies will be added in to highlight what could be implemented in each phase. The strategies added will be the ones mentioned in the previous table. Cross referencing these strategies with the phases discussed in chapter 4.1.2 leads to the following matrix.

	Pre Build	Construction	Use	End of Life
Slow	S1, S2,S3,S4,S5, S6, S10, S12 • Design for Durability & Longevity • Design for Maintenance & Repair • Standardization, Service Models & Warranties	S11, S12 • Encourage Efficiency • Products as a service	S7, S13,S14 • Enable user repair & maintenance • Provide repair & maintenance • Upgrade And adaptability services	S8, S9, S15 • Reuse, Repurpose & Remanufacture Products and components • Turn disposables into reusable services
Narrow	N1, N2, N3, N5 • Design sustainable & lightweight products • Design multipe product functions • Enable and incentivice Resource Efficiency	N6, N7 • Organize light-weight urban transport • Localize supply where appropriate	N8 • Maximize capacity use of products	N4, • Eliminate disposal wate
Close	C1, C2, C3, C4 • Design with and for recyceling • One material components • Design for easy disassembly	C8, C9 • Build with local waste to product loops • Take part with industrial symbiosis	•	C5, C6, C7, C8, C9 • Enable & facilitate resource reuse and recycling • Local resource loops and symbiosis
Regenerate	C1, C2, C3, C4, C8, C10 • Sustainable Material Design • Design with renewable energy integration • Setup projects with sustaining critical ecosystems	C5, C6, C7, C9, C10 • Produce, process and transport using renewable energies. • Build with products that use renewable energies. • Ecosystem regeneration and management	C10 • Manage and sustain critical ecosystem services	C9, C10 • Contribute to regenerating polluted ecosystems • Manage and sustain critical ecosystem services

Table 4: Circularity Matrix

4.2.4 Barriers to Circularity in the BE

According to a systematic review of barriers to circular economy adoption in the construction industry, there are several barriers that impede the transition to a circular economy in the construction industry. These barriers include **financial barriers** such as higher upfront investment costs, **knowledge barriers** such as lack of knowledge, technical capabilities, and expertise in construction, regulatory barriers such as lack of regulatory framework, appropriate policies, and sound legislations for circular economy in construction, and supply chain barriers (Wuni, 2022) (Osei-Tutu, Ayarkwa, Osei-Asibey, Nani, & Afful 2022) (Low et al., 2020).

Wuni(2022), conducted a peer review of several sources and identified 95 Barriers to Circular construction Industry, which were divided into 11 categories. This was analysed and adapted for comparison with other studies. The analysis table can be found in the appendix (appendix table 1)

The transition to a circular economy in the construction industry can bring many benefits, including reduced waste and resource consumption, increased resource efficiency, and reduced environmental impact (Wuni, 2022). The article discusses several taxonomies of barriers to the adoption of a circular economy (CE) in the construction industry. Cultural barriers refer to entrenched ideas, customs and attitudes of the construction industry and its stakeholders that limit the adoption of CE. Market barriers are demand and supply forces in the construction industry that limit CE adoption. Knowledge barriers are skills gaps and knowledge deficits that inhibit CE adoption in the construction industry. Financial barriers are funding challenges, investment constraints and monetary disincentives that impede CE adoption in the construction industry. Management barriers are constraints associated with coordination and administration of tasks to effectively implement circular building and construction projects. Regulatory barriers are steering mechanisms whose availability or unavailability inhibit CE adoption in the construction industry. Technological barriers are constraints associated with limited access to appropriate enabling technologies and tools for CE adoption in the construction industry. Supply chain barriers are constraints associated with organizations, stakeholders, activities, information and resources required to transition to a CE in the construction industry. Stakeholder barriers are impediments associated with people, institutions and organizations who can influence and be influenced by CE adoption in the construction industry. Technical barriers are associated with the level of depth or technical expertise required to implement CE in the construction industry. Organizational barriers are those associated with organizational policy, rules, structure, facilities and cultures inhibiting CE adoption in the construction industry.

The most prominent taxonomies of barriers to CE adoption in the construction industry are knowledge, financial, regulatory, stakeholder, and management barriers. These barriers highlight the need for improved knowledge and understanding of CE among construction practitioners, as well as the need for financial incentives and robust regulatory frameworks to support its adoption. Additionally, effective stakeholder management and strong commitment from top management are crucial for successful implementation of CE practices in the construction industry. In conclusion, addressing these prominent taxonomies of barriers is essential for facilitating the transition to a circular economy in the construction industry .

According to a study by Osei-Tutu et al. (2022), 79 barriers impeding the uptake of circular economy (CE) in the construction industry were identified and categorized into six distinct categories. These categories are cultural barriers, social barriers, environmental barriers, economic barriers, technical barriers, and technological barriers (Appendix table2). The most prominent categories were Economic/Financial Barriers and Technical Barriers. The most occurring barriers identified under the Economic/Financial Barriers category were the high cost of reclaimed materials, low market value, low landfill cost, limited market supply and demand of reclaimed materials, budget and upfront cost, and design cost. The most occurring barriers identified under the Technical Barriers category were limited design codes focusing on reclaimed materials, lack of building design standards for reducing CDW and lack of policy incentives (Osei-Tutu et al., 2022).

According to a systematic literature review by Munaro and Tavares (2023), barriers to the implementation of a circular economy (CE) in the construction sector were classified into five categories: economic, informational, institutional, political, and technological (appendix table 3).

The economic category represented 24% of the barriers and was related to the lack of market investments for effective construction and demolition waste management (CDWM). The main barrier analysed is the lack of marketing strategies for the reinsertion of secondary materials (Akinade et al., 2019; Campbell-Johnston et al., 2019; Tomaszewska, 2020).

The informational category (10% of the barriers) is related to negative perception, lack of knowledge, and dissemination of circular actions to society. The lack of awareness and consumer demand is a widely recognized barrier to the implementation of the CE in the sector (Campbell-Johnston et al., 2019).

In the institutional category (15% of the review barriers), cultural barriers of the sector were addressed due to the slow nature of changes and complex and competitive supply chains. The understanding of the CE concept is a gap in organizational dimensions, such as lack of incentives for actors towards circularity.

The political category represented 27% of the reviewed barriers and addressed government's lack of support for an efficient regulatory system to encourage integrated resource management and Design for disassembly (DfD). Existing resource policies emphasized efficient use of resources rather than reducing demand for resources (Hossain et al., 2020).

The technological category (24% of the review barriers) addressed issues such as lack of a construction design standard to reduce waste, low cost for CDW disposal, and inadequate urban planning. These issues correlate with lack of guidance for effective collection and classification of CDW, immature recycling technology, and underdeveloped market for secondary materials (Huang et al., 2018; Kanters, 2020).

Overall, political and technological categories were found to be most influential in implementing CE in the construction sector (Munaro & Tavares, 2023).

Bases on the exhaustive literature reviews stated a summary table was created (table 4).

The systematic review of barriers to circular economy adoption in the construction industry reveals several categories of barriers that impede the transition to a circular economy. These barrier categories include economic/financial, technical, cultural, social, environmental, informational, institutional, political, and technological barriers. Among these categories, the most prominent and frequently mentioned barriers are economic/financial barriers and technical barriers.

The economic/financial barriers encompass challenges such as high upfront investment costs, low market value of recycled materials, limited market supply and demand for reclaimed materials, and the high cost of reclaimed and recycled products. These barriers highlight the need for financial incentives, access to funding, and the development of market mechanisms for the recovery and reuse of materials.

The technical barriers involve constraints related to design codes, building design standards, policy incentives, and technological infrastructure readiness. The lack of design standards for reclaimed materials, insufficient application of the 3R approach (reduce, reuse, recycle), and inadequate technology for recycling and reuse hinder the adoption of circular practices in the construction industry.

While economic/financial and technical barriers are the most prominent, other barrier categories such as cultural, social, environmental, informational, institutional, political, and technological barriers also play significant roles in impeding the adoption of circular economy practices. These categories encompass factors such as resistance to change, lack of awareness and knowledge, inadequate regulations and policies, limited collaboration and communication among stakeholders, and insufficient technological know-how.

In terms of the hierarchy of importance, it is essential to address all barrier categories as they are interconnected and can influence one another. However, the prominence of economic/financial barriers suggests the need for financial incentives, support mechanisms, and market development to create economic viability for circular construction practices. Additionally, addressing technical barriers is crucial to enable the implementation of circular designs, technologies, and processes.

Furthermore, cultural and social barriers need to be overcome through awareness campaigns, education, and a shift in societal perceptions towards reclaimed and recycled materials. Regulatory and institutional barriers should be addressed by developing appropriate policies, regulations, and support frameworks that promote and facilitate circular practices in the construction industry. Finally, technological barriers require investments in research, development, and implementation of innovative technologies and tools that enable the efficient recovery, reuse, and recycling of materials.

In conclusion, addressing the various categories of barriers, with particular attention to economic/financial and technical barriers, is vital for the successful adoption of a circular economy in the construction industry. Overcoming these barriers will pave the way for reduced waste, increased resource efficiency, and minimized environmental impact, leading to a more sustainable and resilient construction sector.

Barrier Categories	Barriers
Cultural	- Hesitant company culture and change resistance - Lack of interest in recycled and remanufactured products - Reluctance and risk aversion of construction stakeholders - Perceived poor quality of refurbished and recycled products - Preferences of virgin construction materials over reused and recycled products - Absence of CE and sustainable cultural behaviour
Market	- Lack of market pressure and competition - Uncertain market demand for refurbished, remanufactured, and recycled products - Immaturity of market and relevant technologies - Limited availability of recycled materials and reused products - Lack of market mechanisms for waste recovery - Poor demand for environmentally superior technologies
Knowledge	- Lack of CE knowledge, technical capabilities, and expertise in construction - Limited stakeholder awareness of circular materials, products, services, and strategies - Limited CE awareness across the construction supply chain network - Lack of appropriate CE training, development programs, and technical support - Lack of data and information on circular construction materials, products, and services - Insufficient understanding of the benefits of circular materials and products
Financial	- Higher upfront investment costs - Lack of funding for circular business models - Lack of capital financial resources - Lack of economic benefits in the short run - Low prices of virgin materials - Unpredictable financial returns and economic savings - High cost of eco-friendly materials and products - Unclear financial business case for CE construction
Management	- Lack of top management commitment, support, and leadership - Lack of standard indicators, systems, and data collection for performance assessment - Limited circular designs in construction projects - Lack of successful business models and frameworks to implement circular construction projects - Complex planning requirements and management processes - Lack of design tools and strategies for circular business models and circular products
Regulatory	- Lack of a regulatory framework and appropriate policies for CE construction - Lack of government financial support mechanisms and tax incentives - Lack of regulatory pressure and stringent regulations - Lack of clearly defined national goals, targets, and visions for CE construction - Lack of sound infrastructure for CE construction - Poor institutional support framework for CE construction - Weak enforcement of rules and regulations for environmental protection - Lack of incentives for designing end-of-life products
Technological	- Lack of technology infrastructure readiness - Lack of proven technologies and equipment for CE construction - Lack of robust information systems to track recycled materials - Lack of technological eco-innovation capacity - Lack of enabling digital technologies and solutions - Limited technology design for end-of-life products

Supply Chain	- Fragmentation and complexity of the CE supply chain network in construction - Lack of collaboration and communication among stakeholders in the supply chain - Inadequate logistics and transportation infrastructure for recycled materials - Limited availability and accessibility of local recycling facilities and centres - Inefficient waste management practices in the construction industry - Lack of standardized processes and certifications for recycled materials - Difficulty in tracking and verifying the origin and quality of recycled materials - Incompatibility of construction materials and components for circularity - Challenges in reverse logistics and product take-back systems
Legal	- Regulatory barriers and constraints on using recycled materials and circular products - Lack of legal framework for promoting circular economy practices in construction - Unclear liability and responsibility for the performance and safety of reused and recycled materials - Limited legal protection for innovative circular business models - Complex permitting processes for using recycled materials in construction projects - Insufficient enforcement of laws and regulations related to waste management and recycling - Intellectual property rights issues related to circular innovations in the construction industry
Environmental	- Lack of awareness of the environmental impact of construction activities and the potential benefits of circular practices - Insufficient understanding of the life cycle environmental impacts of construction materials and products - Limited availability of environmentally friendly construction materials and technologies - Lack of environmental assessment tools and standards for circular construction - Challenges in measuring and quantifying the environmental benefits of circular practices - Limited consideration of carbon footprint and embodied energy in construction decision-making - Lack of integration between circular economy and sustainable development goals in the construction industry

Tabel 4: Summary table circularity barriers

4.3.5 Role of technology

According to Bocken et al (2020), refers to a fifth supporting strategy, which supports the previous four strategies. This was the Information strategies.

"informing" refers to using information technology as a support strategy for the circular economy (Konietzko, Bocken, Hultink, 2019; Pagoropoulos, 2017; Kerin & Pham, 2019; Morlet, Blériot, Opsomer, Linder, Henggeler, Bluhm, Carrera, 2016; Bocken, Ingemarsdotter, Gonzalez, 2019). We include this support strategy because several practice and research projects have highlighted the importance of information technology for a circular economy. For example, the role of artificial intelligence (Ellen MacArthur Foundation, 2019), the Internet of Things (Morlet, Blériot, Opsomer, Linder, Henggeler, Bluhm, Carrera, 2016; Bocken, Ingemarsdotter, Gonzalez, 2019), big data (Nobre & Tavares, 2017), or online platforms (Konietzko, Bocken, Hultink, 2019).

While using information technology may support higher environmental sustainability, it can also lead to adverse effects (Xu, Cai, Liang, 2015; Hribernik, Ghrairi, Hans, Thoben, 2011), for +example, regarding the higher energy use requirements of digital infrastructure (Xu, Cai, Liang, 2015). It is therefore important to highlight that information technology needs to be viewed as a means to an end (in this case, circularity), and not as an end in itself. The ability of information technology to enable circularity therefore requires thorough assessments to understand its potential to reduce overall environmental impact.

Most principles that can inform material and energy flows may support more than one circular strategy. A product principle to inform flows is, for example, 'design connected products' (Pagoropoulos, 2017; Bocken, Ingemarsdotter, Gonzalez, 2019). Connected products can slow flows by informing maintenance and repair needs. Delta Development, for instance, as part of their product-as-a-service model, has sensors in some of their elevators to inform maintenance needs (Bocken, Ingemarsdotter, Gonzalez, 2019). Connected products can also help to close flows by knowing the location of products at the end of their lives (Bocken, Ingemarsdotter, Gonzalez, 2019).

A business model principle for informing is 'track the resource intensity of the product-in-use.' Philips, for example, uses sensors in some of their lighting devices to track data on how their lights are used within their 'lighting-as-a-service' model to save electricity (Xu, Cai, Liang, 2015). An ecosystem principle to inform flows is to 'operate service ecosystems via online platforms' (Konietzko, Bocken, Hultink, 2019). An example is the online platform Whim, which operates mobility-as-a-service ecosystems in cities that include different private and public modes of transportation (Bocken, Short, Rana, Evans, 2014).

4.3 Digital Twins

Because of its potential to improve project management, safety, and facility management, digital twin technology has attracted substantial attention in the construction sector (Eastman et al., 2008; Shafiq & Afzal, 2020; Lu et al., 2019). It entails creating a virtual replica of a physical asset, such as a building or infrastructure, that may be used for a variety of functions during its existence (Shafiq & Lockley, 2020; Park & Kim, 2015).

Digital twins provide various advantages in the construction sector, including greater safety, collaboration, and efficiency (Patacas et al., 2016; Dixit et al., 2019; Ferguson et al., 2017). It enables stakeholders to see and simulate various situations, as well as detect potential concerns and optimize the design and construction processes (Khajavi et al., 2019; Lockley et al., 2013).

Digital twins are also utilized in facility management to help validate and visualize asset information models (AIM) (Parmar et al., 2020; Brilakis et al., 2019). They allow building owners and facility managers to access and analyse real-time data, monitor performance, and make educated maintenance and operations decisions (David et al., 2018; Grieves, 2016).

Digital twins emerged from the domains of aeronautical engineering and cyber-physical systems (Haag & Anderl, 2018; Glaessgen & Stargel, 2012). It has since spread to other industries, such as manufacturing and smart cities (Chen, 2017; Qi & Tao, 2018). The integration of digital twins with technologies such as the Internet of Things (IoT) and artificial intelligence (AI) boosts their capabilities even further (Madni et al., 2019; Zheng et al., 2018).

Finally, digital twin technology has the potential to transform the construction sector by allowing stakeholders to develop and interact with virtual versions of physical assets. It provides various advantages, including increased safety, collaboration, and efficiency. As the technology evolves and matures, its applications are projected to spread across other disciplines.

4.3.1 Definition Digital twins

A Literature review by van der Valk, Haße, Hendrik, Möller, & Otto (2022) also discusses the possible different iterations of digital twins. It states that Data-linked digital twins connect actual and virtual items. Digital Twins are yet poorly defined. Digital Twins have many configurations due to different use cases. Wagner et al. (2019) note that Digital Twin definitions vary by use scenario. Digital Twins in healthcare require different qualities than in manufacturing (Rivera et al., 2019; Kritzinger et al., 2018). Real-time updates are a common factor amongst digital twins, however this does not take into account the latency requirements for different digital twins for various purposes. In the study by van der Valk et al, (2022) interview partners described their own Digital Twins to ensure use case independence. One respondent used a Digital Twin to capture, validate, and maintain master data, while another used it to improve warehouse transparency and process analysis. Digital Twins were also used in production, product monitoring, healthcare, and supply chain management.

Digital Twins are complex and contextual due to their lack of a specific definition and wide variety of uses and their ideal configurations for different use cases need more research. One definition of a Digital Twin proposes it as a virtual representation that integrates data inputs, handles and processes data, and establishes a bi-directional data linkage between the virtual and physical worlds. Synchronization is crucial to reflect changes in the physical object's state. Recent reviews, such as Kritzinger et al. (2018) and Errandonea et al.

(2020), emphasize the importance of automatic data linkage in a Digital Twin. However, there are instances where so-called Digital Twins lack this automatic data flow.

Sultan Cetin et. Al, (2022) in their article did not appear to provide a definition of digital twin beyond digital twins being A **digital twin** is defined as a **virtual representation** of an object or system designed to accurately reflect a physical object. They however did state that the digital twins are created through the use of technologies. This perspective of a network of technologies is relevant as it provides not only a use case or firmware perspective of digital twins but also the hardware and capability perspective. For this thesis therefore a combined perspective on the definition will be given that considers the physical network and the software components to provide interviewees with a holistic description of a digital twins. Based on this networked perspective additional literature will be gathered to generate an independent overview of possible configurations. This will be done in the next section.

Based on these descriptions the following definition of digital twins will be used in this thesis. Based on apparent consensus in the Architecture, Engineering, Construction, and Operations (AECO) industry, a digital twin is a virtual representation of a physical asset, reflecting the real-world entity it models. A key characteristic of a digital twin is its connection to the physical part, allowing it to adapt and reflect changes over time. Importantly, digital twins are not limited to the software component alone; they also encompass the physical assets they represent, forming an integrated system of both digital and physical elements. In the AECO sector, the physical component includes built assets such as residential and commercial buildings, hospitals, bridges, tunnels, and industrial factories, while the digital component typically consists of a three-dimensional (3D) model containing linked information relevant to the physical asset. Furthermore, there are varying configurations of digital twin networks depending on their specific use cases, with different technologies and platforms integrated to suit the particular requirements of monitoring, analysis, or lifecycle management.

Based on a literature review van der Valk, Haße, Hendrik, Möller, & Otto (2022), highlight four different types of Digital twins. This is based on the functionality of the Digital twins. These Definitions are based on functionality and reliant on other technologies, both of which will be discussed further the following analysis.

4.3.2 Digital Twins Archetypes

In this chapter we will discuss the variables (factors), which based on sevral dimensions create different Digital twin Typologies. the categorization into mandatory, mutually exclusive, not relevant, and optional is based on the literature review and from an understanding derived from the expert's insights. In the following, we will describe the different dimensions along with their classification into the meta dimensions **data collection, data handling and distribution, and conceptual scope.** Van der valk et. Al (2022) derived the meta-dimensions inductively based on the dimensions' perceived similarity to each other (Bronowski 1953).

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Table 4 Taxonomy of digital twins (M = mandatory, ME = mutually exclusive, N = not relevant, O = optional)

Meta-Dimension	Dimension	Characteristic			
Data Collection	Data Acquisition	Automated (M)		Semi-Manual (O)	
	Data Source	Multiple Sources (M)		Single Source (N)	
	Synchronization	With (M)		Without (N)	
	Data Input	Raw Data (M)		Preprocessed Data (O)	
Data Handling and Distribution	Data Governance	Rules Applied (ME)		Rules Not Applied (ME)	
	Data Link	Bi-Directional (M)		One-Directional (N)	
	Interface	HMI (O)		M2M (O)	
	Interoperability	None (ME)	Via Translator (ME)		Fully (ME)
	Purpose	Processing (M)	Transfer (O)		Repository (M)
Conceptual Scope	Accuracy	Identical (N)		Partial (N)	
	Conceptual Elements	Independent (N)		Bound (N)	
	Time of Creation	Digital First (N)	Physical First (N)		Simultaneously (N)

Figure 4: Variables connected to Digital twins in relation to Meta Dimensions (van der Valk et, al. 2022)

The meta-dimension **Data Collection** describes all processes. to collect data. This category's dimensions are data acquisition, data source, synchronization, and data input.

Some descriptions of Digital Twins merely mention a manual or semi-manual data acquisition (Miller et al. 2018). However, it was apparent that most publications only describe an automated data acquisition, e.g., through sensors (Cai et al. 2017). The research conducted (Van der Valk et. al, 2021) showed the contrast between the literature and the industrial opinion, as a semimanual data acquisition was demanded. Mandatory is the need for automated data acquisition.

In this context, single data sources do not mean that just one device gathers data, but that only one type of device, e.g., sensors, is used. Multiple data sources include different types of sources. A Digital Twin used in practice cloud use data from the sensors attached to an asset, historical sensor data from a database and external conditions during the assets lifetime. This is often the case with digital twins. As most definitions mandate a synchronization between the Digital Twin and the physical part, the option of without synchronization is somewhat surprising (Kritzinger et al. 2018). Nevertheless, there are some examples in which a Digital Twin is described as a not synchronized digital object (e.g., Banerjee et al. (2017), Grube et al. (2019)). However, concepts without any kind of synchronization contradict definitions given above. This mean s it is an essential aspect of Digital twins.

We distinguish between raw and pre-processed data. Raw data is unprocessed data. These data may stem from sensors, data collection devices, or databases. (Pre-)processed data contains all data which comes from software tools, i.e., analytical tools, applications, or smart devices. In most cases, the Digital Twin integrates both data types for internal data processing (Boschert and Rosen 2016; Shangguan et al. 2019).

The meta-dimension **Data handling and distribution** deals with the dimensions data governance, data link, interface, interoperability and the purpose of a Digital Twin.

Data governance is one of the most critical aspects of data flows (Otto and Weber, 2018). Data governance was an umbrella term for everything related, e.g., data security, data sovereignty, or access control. Van der Valk et. al, (2022), divided this dimension into rules applied or not applied. The dimension data governance was highlighted as very relevant during the interviews, and suggestions for extensions to more detailed sub dimensions, e.g., ownership of the Digital Twin, data accessibility, cyber-security, or data quality management, were provided for further research.

The flow of data is an important aspect of Digital Twins (Van der Valk et. al, (2022). These can be either one directional (data flows from an asset to digital twin) or bi-directional (data flows from physical asset to the twin which gives feedback to the physical asset). A bi-directional link has great utility as it allows for autonomous monitoring and management. Furthermore, data links can be chained into a network of assets. This can also be seen as a network of sub assets that act as sources for a physical twin of a larger asset.

Van der Valk et. al, (2022), highlighted two ways that data leaves the Digital Twins. In contrast to the Machine-to-Machine interface for data input, they addressed the Human machine Interface for access to data output (i.e. through dashboards, AR technologies etc.). The second way to access data outputs from digital twins is a Machine-to-Machine interface, which can allow for autonomous management of a digital twin and asset. Notably Petrova- Antonova and Ilieva, (2019) stated that these two methos are not mutually exclusive.

Many companies state problems in safety-relevant, infrastructural sectors with machine-to-machine interfaces when it comes to the interviews. Exemplarily, direct integration with a digital tool via machine to machine-to-machine interfaces is forbidden.

From interviews conducted Van der Valk et. al, (2022), it became clear that interoperability is a necessary aspect of the digital twins. It guaranteed standards for the exchange of data and allows Digital twins to integrate data processed or retrieved from a variety of sources. The dimension of purpose encompasses a range of possible uses for Digital Twins, these include tasks such as Simulation, Condition Monitoring and Analysis, Forecast and Prediction, Optimization, Representation, Data Transfer and Storage, Controlling, Machine Learning, Decision Making, and Cost Reduction (Van der Valk et. al, 2021). These tasks can be grouped into data processing, data transfer, and repository categories, which can coexist in a Digital Twin.

The final Meta-Dimension was the **Conceptual scope** and encompasses accuracy, conceptual elements, and time of creation.

Accuracy deals with the degree to which a Digital twin represents a physical asset. These can be identical or partial representations with the first being the being fully identical and the second only containing the necessary elements of the twin. The first case is unlikely and the second is dependent on the use of the twin.

The conceptual element refers the two-element making up the relationship of physical asset and digital twin. There are two possibilities are available here physically independent, referring to virtual representations and physically bound, referring to twins tied to an asset. Van der Valk et. al, (2021), states that digital twin's states that this is not relevant for the twin's functionality.

Time of creation refers to the time when the digital twin was created in comparison to when the digital twin was created. This leads to three variations namely digital first, physical first and simultaneous. Boschert and Rosen (2018), states that Digital twins are designed after the physical asset.

Below the types of digital twins are identified through the review of literature. Based on interviews and literature Van der Valk et. al, (2021), states that the mandatory characteristics are as follows, Automated Data Acquisition, Data from Multiple Sources, Synchronization with the physical asset, Raw Data Input, Bi-Directional Data Link and a Purpose as a Processing and Data Repository tool.

The AT 1 in the paper of Van der Valk et. al, (2021), High lights it as a basic Digital twin with only a Human machine interface incorporated.

AT2 Adds integrated access to pre-processed data from software tools, i.e., analytical tools, applications, or smart devices. Furthermore, it has the ability to semi-automatically acquire data.

The AT 3 expands this by providing autonomous control capabilities while also including a human-machine interface that allows for potential intervention. Given the feasibility of establishing direct connection with another machine, whether in a virtual or physical context, it is essential for this archetype to possess a minimum level of interoperability via the use of a translator interface.

The AT 4 adds the ability to exercise control over the physical asset and can allow external processing of data gathered by the digital twins. This type however does not have a direct Human machine interface as it is meant to automate control over a physical asset.

The last architype AT 5 is the exhaustive digital twin, which includes all relevant options for data acquisition, processing and providing both monitoring and control capabilities.

4.3.3 Digital twin Sub-Technologies

The notion of Digital Twins (DT) included a range of technologies, including Building Information Modelling (BIM), cloud computing, Internet of Things (IoT) sensor networks, 3D scanning, construction simulation, and 3D scanning. It is important to note that there was no singular programme specifically designated as 'DT software' (Tobias, 2019). In the following chapter we will discuss the different technologies which can be seen as enabling subcomponents of digital twins.

BIM

Building Information Modelling (BIM) is a digital representation of the physical and functional characteristics. Building Information Modelling (BIM) is a widely acknowledged and extensively used digital technology that serves as a representation of both the physical and functional attributes of a building (Khajavi et al., 2019). As previously stated, the development of Digital Twins (DT) originated from Building Information Modelling (BIM) and was further enhanced by the integration of sensing capabilities, big data, and Internet of Things (IoT) information (Boje et al., 2020). Nevertheless, it was mostly used during the first phases, with a decreasing frequency of utilisation in subsequent stages, such as maintenance and operation (Eadie et al., 2013). Despite its limitations, this technology remains a well-developed tool that facilitates information circular design and realisation, collaboration, and process management (Singh et al., 2011). In addition to the incorporation of 3D modelling, Building Information Modelling (BIM) encompasses the integration of building requirements, time schedules, cost projections, and maintenance management, which are represented by 4D, 5D, and 6D BIM. Following the completion of the delivery process, the Building Information Modelling (BIM) system has the potential to be used throughout the usage stage via its integration with a sensor network, as suggested by Khajavi et al. (2019).

Cloud computing

Cloud computing refers to the delivery of computing services, including storage, processing power, and software applications, through the internet. During the feasibility stage, it is possible to develop an integrated platform using cloud computing to include comprehensive historical and real-time data pertaining to the urban setting. The text provides an illustration of the many players' actions within the supply chain and their impact on the urban environment. In this particular scenario, the establishment of a digital twin (DT) can be associated with the concept of a smart city DT. This association facilitates several key benefits: Firstly, it allows for the accurate understanding of clean energy (CE) regulations by leveraging historical databases within the smart city. Secondly, it promotes public awareness of climate change (CC) through user-friendly visualisation tools. Lastly, it facilitates the exchange of market intelligence and advancements by fostering interaction among different components of the city.

Cloud computing has the potential to provide a comprehensive platform across the many phases of a project's lifecycle. This platform would enable seamless and productive information sharing inside the project organisation. Consequently, it would enhance cooperation among diverse stakeholders involved in the projects (ARUP, 2019).

3D Scanning * add sensors

The process of 3D scanning involves capturing the physical attributes and geometry of an object or environment using specialised equipment and techniques. The objective of adaptative refurbishment in the context of existing projects is to replicate the present installations with a high level of accuracy. The use of 3D scanning, in conjunction with the Internet of Things (IoT), proves to be quite advantageous for this particular undertaking. Hence, it is crucial throughout the utilisation phase (ARUP, 2019).

The Internet of Things (IoT)
The subsequent phase in the construction of a decision tree model subsequent to using BIM 3D modelling involves the incorporation of Internet of Things (IoT) sensors for the purpose of gathering real-time data. The Internet of Things (IoT) serves as a foundational framework for assessing the outcomes resulting from the activities of different stakeholders during the lifespan of tangible goods, using a dynamic feedback control loop. The use of material information may also be applied in the context of supporting materials passports after the end-of-life stage (Pagoropoulos et al., 2017).

Material Passports

The material passport is a comprehensive method at the micro-level that utilises the notion of Design Thinking, extending beyond the boundaries of the project life cycle. The objective is to address the disparity in resource allocation across the supply chain. Through the identification of materials being used and the updating of information on an information platform, the supply chain achieves transparency, resulting in the equilibrium of supply and demand. As more resources were uncovered, the process of obtaining and using secondary materials grew more convenient and appealing, leading to improved accessibility and a heightened understanding of their significance.

The process of identification has the potential to enhance on-site construction by giving detailed information about the components involved. On-site sorting of demolition trash has the ability to optimise the upcycling process and facilitate the documentation of attributes associated with secondary materials. The good management of the complicated supply chain may facilitate the closure of the material loop (ARUP, 2019; Benachio et al., 2019; Rocca et al., 2020; Patterson & Ruh, 2019; Ghaffar et al., 2020).

Artificial Intelligence

AI is "the ability of a computer or machine to mimic the capabilities of the human mind" (IBM, nd) and has various subbranches using different methods. Machine Learning trains algorithms to learn from data and find patterns for decision making with minimal supervision, while Deep Learning can train itself for particular tasks (IBM, 2023). AI can improve design, infrastructure, and circular business models for CE transitions, according to EMF and Google (Ellen MacArthur Foundation & Google, n.d.). Circular BEs can use similar AI skills.

There is possibility of design optimization bases on performance criteria, for example circularity, (Ellen MacArthur Foundation & Google, n.d.). Płoszaj-Mazurek et al., (2020) presented a machine learning model that predicts impact of circular building projects. When used in conjunction with other technologies such a big data and the internet of things AI could allow be used to detect and predict the state of assets. In this case sensors such as computer vision components paired with deep learning could use past data to predict future state of assets (Arcadis 2020). The FaSA application utilises artificial intelligence, drone, and sensor technologies to assess the present condition of buildings and forecasts the maintenance needs of their façade components (Facade Service Applicatie, n.d.). Deep learning models could also be used to, based on previous demolition data, make predictions of the amount of reusable material in buildings. (Akanbi et al., 2020). Furthermore Rakshan et al., (2020), proposed that predictive models could evaluate the reusability of recycled elements, and Davis et al., (2021) stated that similar technologies could be used to evaluate recycle ability of assets at demolition sites when used in conjunction with sensor capabilities. When providing these algorithms and applications with the vast, accurate, historical and current data stored within digital twins the capabilities to evaluate and predict more accurately, not only on certain parts but entire buildings. Also, it provides actors with the capability identify what is worth recycling and asses what methods would be needed as to not damage assets.

Digital Material Platforms

A digital platform is understood as a software-based system providing core functionalities upon which derivative applications can be developed, while non-technical perspectives see it as a multi-sided network, matching different groups of users to exchange goods and services (Asadullah et al., 2018).

From a CE point of view, Konietzko et al. (Konietzko et al., 2019) put forward three essential functions that online platforms deliver for narrowing, slowing, and closing resource loops: first, digital platforms act as virtual markets, allowing access to and the exchange of goods; second, they facilitate the operation of product-service systems, enabling data collection for maintenance and repair; third, they empower people to co-create circular products and services.

Cetin et al. (2021), highlighted the use of Digital platforms to act a tool to create circular ecosystems for circular built environment by connecting business to businesses and businesses to consumers. It provided examples of a platform for the exchange of excess materials and waste between businesses (Excess Materials Exchange, n.d.) and marketplace for consumers to access leftover material (Enviromate, n.d). Additionally, platforms could also act as repositories and tools for sharing information about materials, kept up to date through connections with existing physical assets. Such a platform was proposed by Xing, Kim, & Ness (2020). A comparable tool analyses the circularity index of construction projects and registers data on buildings, goods, and materials (Madaster, n.d.). Similarly, Yu et al., (2021) Proposed a system which allowed for different stakeholders to track, evaluate and negotiate the flow of materials and Kovacic, Honic, & Sreckovic,(2020) proposed a platform which explicitly is meant to do this through the entire life cycle of buildings.

It should be stated that compared to the other edge technologies these digital marketplaces can be seen as less integrated and are meant to receive data from digital twins. The technologies above could be networked into the twins.

Cetin et al. (2022), also references Digital Market places as another technology that can function as an edge technology. It should be stated that compared to the other edge technologies these digital marketplaces can be seen as less integrated and are meant to receive data from digital twins. The technologies above could be networked into the twins.

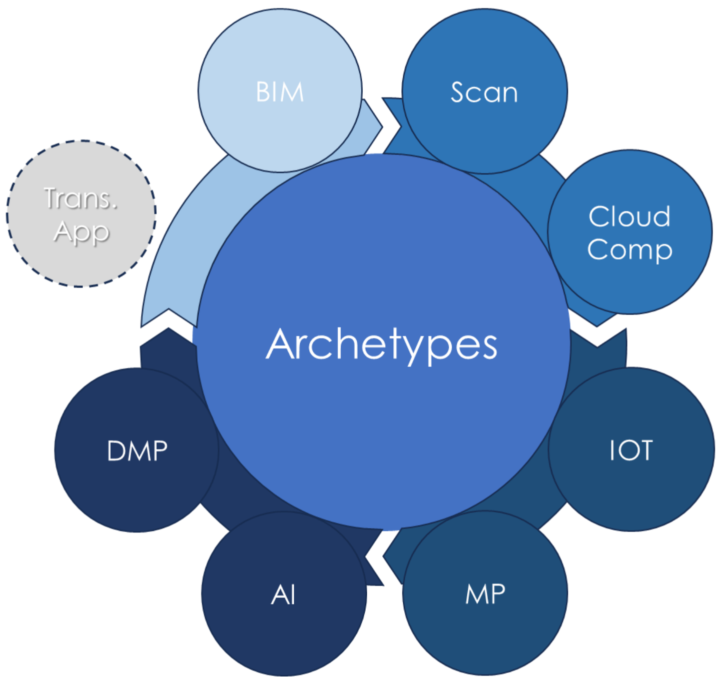

Figure 5: Digital Twins as a network of sub technologies

4.3.4 Sub-Components of Digital Twins

Based on these descriptions of potential edge technologies certain archetypes could integrate several edge technologies. These are illustrated in the table below.

Archetype	BIM	Cloud Computing	3D Scanning	Internet of Things (IoT)	Material Passports	AI	Digital Material Platforms
AT 1	Yes	No	Yes	No	yes	No	No
AT 2	Yes	Yes	Yes	Yes	Yes	No	No
AT 3	Yes	Yes	Yes	Yes	Yes	Yes	No
AT 4	No	Yes	Yes	Yes	Yes	Yes	No
AT 5	Yes	Yes	Yes	Yes	Yes	Yes	Yes

This table illustrates which edge technologies are relevant to each archetype (AT). "Yes" indicates the technology is relevant to that archetype, while "No" indicates it is not. The relevance may vary depending on the specific capabilities and objectives of each archetype within the digital twin context.

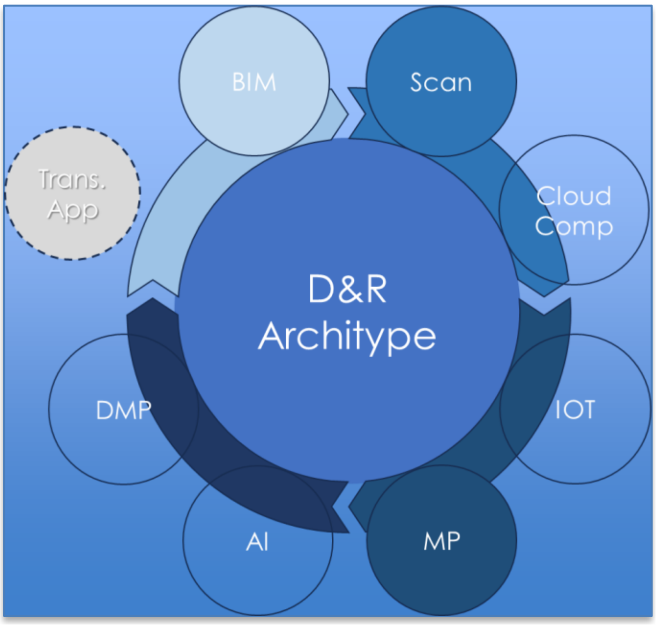

Figure 6: Archetype 1

AT 1: Design & Repository Twin

This first digital twin is based on acting as a tool for storing data gathered from a building and as a way for actors to interact with digital representations of buildings for example for design purposes.

- BIM – This component is present in the form of a representational tool for Human Machine interfacing.
- 3D scanning- This tool is present in the form of Data Input via sensors and other technologies meant to create data stored in Digital Twins
- Material Passports - These are present as incorporated subcomponents of the twin allowing for storage and access to granular data for the subcomponents of buildings

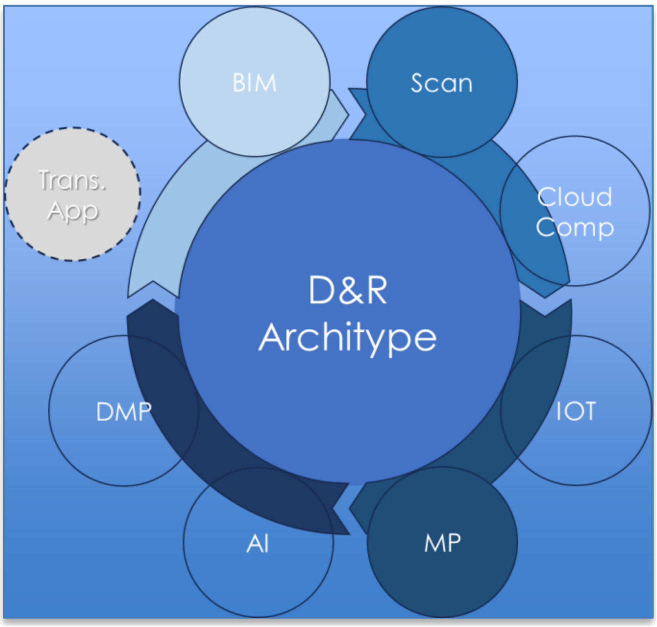

Figure 7: Archetype 2

AT 2: Basic Analysis Twin

The second archetype this focused on not only storing data and allowing actors to interact with it, but it's also meant as a tool for analysing the created digital twin. To this end cloud computing and an Internet of Things connection are necessary to analyse an existing representation and to properly indicate the effect of potential changes whilst also taking into consideration external factors.

- BIM – This component is present in the form of a representational tool for Human Machine interfacing.
- Cloud computing – this tool is present in the form of computational applications that are capable for example to analyse the circularity of certain materials.
- 3D scanning and sensors - This tool is present in the form of Data Input via sensors and other technologies meant to create data stored in Digital Twins
- IOT – Access to outside supplementary and external sources of data sources of data and data based on external actors.
- Material Passports - These are present as incorporated subcomponents of the twin allowing for storage and access to granular data for the subcomponents of buildings

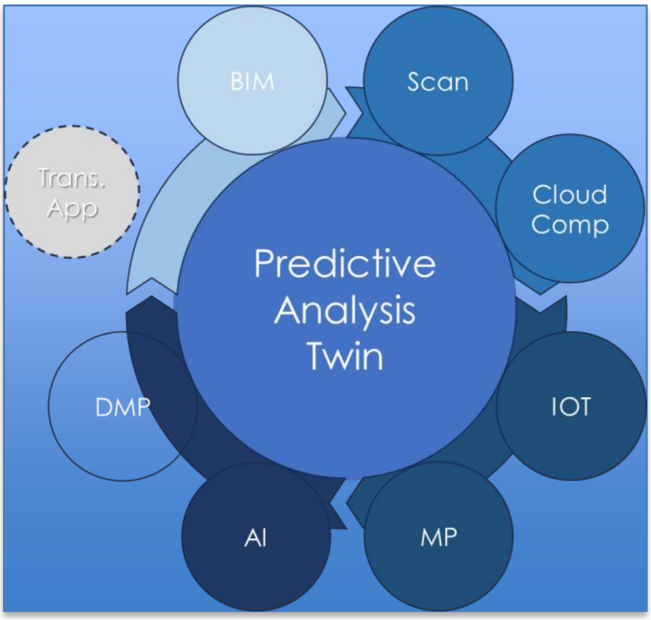

Figure 8: Archetype 3

AT3: Predictive Analysis Twin

The third archetypes are more advanced the goal of these types of digital twins this to add a predictive layer to the capabilities of the digital representations. These digital representations act as design, data storage, analytical and predictive tools for digital twins. AI can be used to predict the state of components and subcomponents allowing them to facilitate multiple circularity strategies.

- BIM – This component is present in the form of a representational tool for Human machine interfacing.
- Cloud computing – this tool is present in the form of computational applications that are capable for example to analyse the circularity of certain materials.
- 3D scanning and sensors - This tool is present in the form of Data Input via sensors and other technologies meant to create data stored in Digital Twins
- Material Passports - These are present as incorporated subcomponents of the twin allowing for storage and access to granular data for the subcomponents of buildings
- IOT – Present as a way to access external data, for access to data from external actors and provide potential access for human machine interaction.
- AI – Can be present in both an integrated and external capacity as this architype uses both data processed internally and externally. Furthermore, Autonomous data acquisition, processing and categorisations of materials could be done through this technology however through human input standards and priorities could still be set.

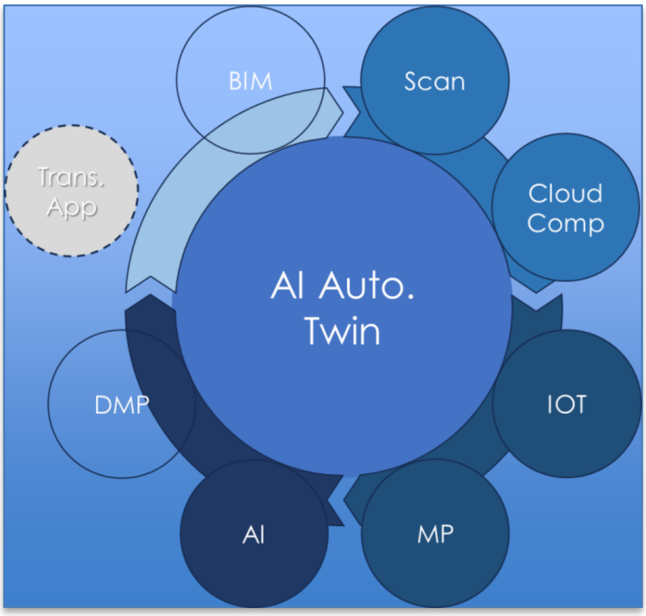

Figure 9: Archetype 4

AT4: AI Automated Twins

Archetype 4 removes the human interface but adds an additional capability to share information across digital twins directly. It could facilitate data storage analysis predictions and sharing; however, the use cases will be limited as in the near future it is apparently unlikely that humans will be completely removed from the processes within the built environment.

- Cloud computing – this tool is present in the form of computational applications that are capable for example to analyse the circularity of certain materials.
- 3D scanning and sensors - This tool is present in the form of Data Input via sensors and other technologies meant to create data stored in Digital Twins.

- Material Passports - These are present as incorporated subcomponents of the twin allowing for storage and access to granular data for the subcomponents of buildings
- IOT – Present as a way to access external data based on non-integrated platforms.
- AI – Can be present in both an integrated and external capacity as this architype uses both data processed internally and externally. Furthermore, Autonomous data acquisition, processing and categorisations of materials could be done through this technology. Furthermore, based on for example learning algorithm's standards and priorities could be set autonomously for the end of life phase and even demolition strategies could be independently produced.

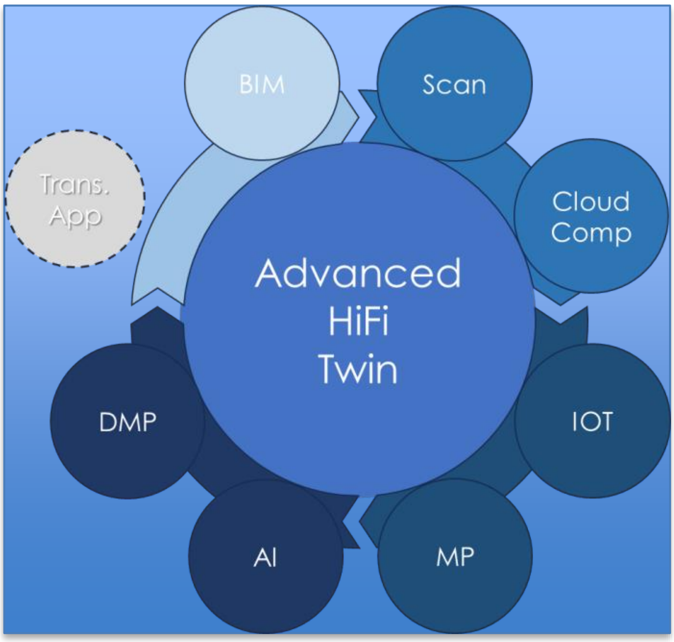

Figure 10: Archetype 5

AT 5: Advanced High fidelity Twins

Architect five, as stated earlier is most comprehensive digital twin architype. This archetype much like archetype four, has the capacity to share information and integrate shared information. It's integrated AI capabilities paired with cloud computing create a powerful tool for analysing I'm predicting component and material flows. It's capacity to share information with other machines and humans either directly or via a material platform allows for an interconnected and integrated digital twin of the larger built environment.

- BIM – This component is present in the form of a representational tool for Human machine interfacing.
- Cloud computing – this tool is present in the form of computational applications that are capable for example to analyse the circularity of certain materials.
- 3D scanning and sensors - This tool is present in the form of Data Input via sensors and other technologies meant to create data stored in Digital Twins.
- Material Passports - These are present as incorporated subcomponents of the twin allowing for storage and access to granular data for the subcomponents of buildings
- IOT – Present as a way to access external data, for access to data from external actors and provide potential access for human machine interaction.

- AI – Can be present in both an integrated and external capacity as this architype uses both data processed internally and externally. Furthermore, Autonomous data acquisition, processing and categorisations of materials could be done through this technology. Furthermore, based on for example learning algorithms standards and priorities could be set autonomously for the end of life phase and even demolition strategies could be independently produced or via human machine collaboration. Sharing of data could also be done autonomously through AI or Human interaction.
- Material Platforms – This is the only architype where an integrated material platform is present as this architype explicitly requires access to provide downstream data. This would however require that multiple digital twins are linked on a significant enough scale. Based on this it could be stated that this twin could need access to downstream data about materials to make informed decisions and suggestions and if given enough authority could create a financial strategy based on listing recycled materials on these platforms.

It should be noted that the description of the architypes above is based on the degree of integration of each of the subcomponents. For example, it could be stated that each of the Archetypes could provide data downstream to material platforms either automatically or through human intervention, but the exhaustive digital twin is the only one where interoperability, the sharing of data and interaction between twins. Meaning it could be considered a network of twins which would need a platform to interact with one another. Even if humans could also access this platform, it could still be considered a way for these machines (Digital Twins) to interact. For Interaction directly between Digital twins, Digital platforms and Humans there is a potential need for a translator Application or tool. This tool could be used to facilitate and enable interoperability and data sharing by adjusting for example data sets regarding materials and components. This could be done through taking raw data stored in material platforms , so not just a certain rating based on circularity standards and translate it to values and standards used by another actor or system.

When considering digital twin architypes there is a factor that impacts the composition of technologies. The age of the structures which the circularity strategies are to be applied to creates a difference in need for the creation of the digital representation. 3D scanning technology is a necessary component. For the creation of digital representations of existing buildings if documentation is insufficient, there is a need for 3D scanning technologies. If the buildings are new construction, there might not be a need for scanning technologies.

According to the European Commission BIM technologies are being increasingly used in the construction processes in the built environment. BIM is used a tool to facilitate modern digital workflows in the realization of buildings. It can be used in all stages of the building process, from conceptual design to realization (Borrmann, König, Koch, Beetz, 2018). It contains at the end of the construction phase not only the geometry of the structure but also detailed information about components and how they are connected. Thus, a 3D scan of a building is not necessary for the creation of digital twins for new buildings. Potentially the twin can be created in conjunction with the design and realization process.

However, 3D scanning technology (Tzedaki and Kamara 2013) might be necessary to update the Digital Twins and add updated data on wear and tear, during the use phase. This is regardless of whether it was an existing or newly built structure. Sensors provide information on the use which can be used for modeling scenarios and wear of components. By tracking use and environmental factors prediction on the state of components, structural elements and materials can be made.

4.3.5 Digital Twins for specific strategies

	Pre Build	Construction	Use	End of Life
Slow	S1, S2,S3,S4,S5, S6, S10, S12 • Design for Durability & Longevity • Design for Maintenance & Repair • Standardization, Service Models & Warranties	S11, S12 • Encourage Efficiency • Products as a service	S7, S13,S14 • Enable user repair & maintenance. • Provide repair & maintenance. • Upgrade And adaptability services	S8, S9, S15 • Reuse, Repurpose & Remanufacture Products and components • Turn disposables into reusable services
	AT1	AT1, AT2	AT1	AT1, AT2, AT 3
Narrow	N1, N2, N3, N5 • Design sustainable & lightweight products • Design multiple product functions • Enable and incentivise Resource Efficiency	N6, N7 • Organize light-weight urban transport. • Localize supply where appropriate	N8 • Maximize capacity use of products	N4, • Eliminate disposal wate
	AT1, AT2, AT3	AT3, AT5	AT3, AT5	AT2, AT3, AT5
Close	C1, C2, C3, C4 • Design with and for recycling • One material component • Design for easy disassembly	C8, C9 • Build with local waste to product loops • Take part with industrial symbiosis		C5, C6, C7, C8, C9 • Enable & facilitate resource reuse and recycling. • Local resource loops and symbiosis
	AT1	AT2, AT3, AT5		AT5
Regenerate	C1, C2, C3, C4, C8, C10 • Sustainable Material Design • Design with renewable energy integration • Setup projects with sustaining critical ecosystems	C5, C6, C7, C9, C10 • Produce, process and transport using renewable energies. • Build with products that use renewable energies. • Ecosystem regeneration and management	C10 • Manage and sustain critical ecosystem services	C9, C10 • Contribute to regenerating polluted ecosystems • Manage and sustain critical ecosystem services
	AT1	AT2, AT3	AT3, AT5	AT5

Table 4: Possible use cases between circularity strategies, phases and archetypes

As discussed in previous paragraphs the digital twin archetypes can be used to facilitate different circularity strategies. In this chapter will be discussed, based on the archetypes defined above, how each of these strategies and each of the archetypes are connected, this whilst still taking into account different phases established in previous chapters for the building life cycle process.

For the slow strategy each of the archetypes is present except for AT4. In the prebuilt phase archetype one it's mostly present this due to the focus on design in this Phase. Standardization service model and warranties are also served by archetype 1, this due to its capability to store information. The storage of raw data identifying information and serial numbers, and other tracking information allows for producers of materials to authenticate materials produced thus creating the capability to locate and to service products. In the construction phase yeah add capabilities of analysing data facilitates a more efficient use of material furthermore as with the first phase the introduction of products as a service is possible due to the capability of the archetypes to store information and translate that for human interaction. During the use phase the capabilities of archetype 1 as a repository for information would be needed. With a focus on repair maintenance upgrade and surface strategies it is imperative that the location the type of material and potential state of material it's available. For the end of life phase there is a focus on reuse and the purpose of components and products this could be done through actions such as recycling but also through the actions of components as a service. For this the capability of predicting would also be needed on top of what was discussed for the previous phases. This is due to the potential need to know in advanced state of materials and components. This would enable actors to predict the state of the materials and know what the return on investment would be, thus allowing for a usable business strategy and ecosystem to be created around these materials and components.

For the narrowing strategy during the prebuilt phase there's once again a focus on design of products and materials however this strategy also focuses on incentivizing resource efficiency from early phases during building life cycles. The capacity to analyse but has been designed for implementation requires the use of archetype 2. For the construction Phase there is a focus on localizing supply and sustainable transport, thus there would be a need for the capabilities of archetype 5. Meaning there would be a need for the added capabilities of shared information [via for example a material platform], access to the future state of materials potentially sourced from local sources and when they would be available. During the use phase for the narrowing strategy the predicting capability would be essential as it would allow materials and components to be used to their fullest extent, by removing potential cases of early replacements or servicing. Also, the sharing of modular building components could also be facilitated. During the end of life phase there is a focus on the elimination of disposal waste. For this would be important the capability to analyse the building. This would allow actors during this phase to know what waste would be produced. An additional layer of complexity would be the addition of predictive capabilities seen in archetypes three and five, which would allow for not only the elimination of waste disposal but efficient sorting of waste through providing a prediction on the state of the materials and components.

For the close strategies, during the prebuilt phase there is once again a focus on design and creation. Thus, once again there is a need for primarily the data repository capabilities and design capabilities through human interaction that the first archetype offers. As stated in the previous paragraph for the construction phase of this access needed to information about other sources of materials and components. This with potentially included when certain materials might become available through the use of predictive algorithms. Thus, once again in this phase there is a need for archetype 3 and 5. During the end of use phase there is a focus on enabling and recycling resources and potentially creating local ecosystems. For this archetype 5 would be the most appropriate, as this archetype can function as a repository for data about a building's components and materials, it can analyse the state of materials, it can predict the future state of materials, and it can share this information with both other digital twins and actors. When creating a local network of digital twins for an areas building infrastructure a research loop can be created. This would potentially reduce the need to introduce new materials into the loop. Tracking predicting and analysing allows for the state of materials to be known and embedded into information linked to each material and component. This could potentially facilitate several end of life activities, for example distinguishing between reusing or recycling materials or components.

Lastly there are the regeneration strategies. He's focused mostly on the impact that each of the phases has on a local ecosystem. In the prebuilt phase this once again they focus on design does there is a need for the capabilities of the first archetype. During the second phase there is both a focus on the use of renewable energies during the process of construction but also as integrated components of the building. The second archetype is needed for its capability to analyse structures, this would benefit allow for efficient transportation of components and materials to the building site. Furthermore, the capability to analyse present in both archetype two and three could be beneficial in the integration of renewable energy components into the building. It could allow for the analysis off to the site, it's orientation surrounding structures and area to create an estimation for the area's energy potential. This could then be integrated into the building's design, thus allowing for a truly energy efficient structure. This could be made more accurate with the introduction of AI predictive capabilities. These AI capabilities should also be needed to assist in ecosystem regeneration and management. For example, based on deep learning algorithms the impact of construction could be predicted based on previous projects. This could then be mitigated thus allowing for a more sustainable construction process with less impact on local environmental ecosystem. The same could be said for the use phase, however in this phase the focus on managing and sustaining critical ecosystems would also benefit from a more widespread adaptation of modern advanced archetypes. This would be the 5th archetype which it's not only built on the analysis and predictive capabilities of one digital twin for one building. It would instead focus on a more widespread adaptation of digital twins for a local areas built environment. This would provide an overview of the current future impact of buildings in use on the local ecosystem. This could then be planned for and mitigated. Lastly the 5th archetype but also be the most useful during the end of use phase. Once again, the use of predictive capabilities, analytical capabilities, data and tracking information and cross machine information sharing seems, and human machine interfacing would be necessary. As stated in previous chapters the end of use phase focuses on for example demolition tasks, thus when considering regeneration strategies for the end of use phase there is a focus on both activities on the building level but also on a more general built environment level. The analytical capabilities of different archetypes allow for demolition strategies to be created, the predictive capabilities allow for these strategies to consider what will happen to materials and components after demolition [for example reuse or recycle], and lastly the sharing capabilities allows for a local ecosystem of material flows to absorb waste effectively and efficiently. Thus, minimizing to waste that enters the environmental ecosystem and avoid pollution. Furthermore, these activities could even integrate more widespread efforts to reduce pollution by pulling waste and pollution already in natural ecosystems into the built environment.

4.3.6 Potentially Solved Circularity Barriers

According to the definition provided by Cetin et al (2021) Digital Twins as defined there could only be used for specific Circular construction strategies, however. Using the definition of digital twins and considering them as a variety networks of the technologies above could provide wider view of the use cases for digital twins. Digital twin in the broadest terms offer the potential capacity to already impact the several of the barriers discussed above.

Digital twins provide various advantages in the construction sector, including greater safety, collaboration, and efficiency (Patacas et al., 2016; Dixit et al., 2019; Ferguson et al., 2017). It enables stakeholders to see and simulate various situations, as well as detect potential concerns and optimize the design and construction processes (Khajavi et al., 2019; Lockley et al., 2013).

Digital twins are also utilized in facility management to help validate and visualize asset information models (AIM) (Parmar et al., 2020; Brilakis et al., 2019). They allow building owners and facility managers to access and analyses real-time data, monitor performance, and make educated maintenance and operations decisions (David et al., 2018; Grieves, 2016).

There are several barriers that potentially could be resolved through the use of Digital Twins. In this chapter we will discuss several of the barriers that could be directly resolved.

First in the market category of barriers to circularity the barriers that could potentially be resolved are:

- Lack of market pressure and competition *
- Uncertain market demand for refurbished, remanufactured, and recycled products *
- Limited availability of recycled materials and reused products *
- Lack of market mechanisms for waste recovery *

Lack of market pressure and competition, uncertainty of demand, lack of availability all are potentially resolved through the use of Digital Twins for circularity. Digital Twins provide an overview materials available and their current and future reusability. When considering the use of material platforms externally or the networked large scale digital Twins with platforms integrated (AT 5) provides a way for materials to visible to outside actors, to be traded efficiently and to from an economy for this trade. Furthermore, Digital Twins in any form when being used Circularity of buildings creates the data that is usable to generate market mechanisms.

The second category is the knowledge barrier to circularity. The barriers potentially solved are:

- Lack of CE knowledge, technical capabilities, and expertise in construction *
- Lack of data and information on circular construction materials, products, and services

The lack of CE knowledge is potentially solved through the simplification of the supply chain. Digital twins could make it easier for actors who don’t use digital twin technologies or whom aren’t yet part of the circular economy to take part. For example, a linear organisation could use simplified information about quality, price and life expectancy to purchase perused or recycled materials. The Data and information shortage will also be solved as Digital Twins create the ability to store and generate this information.

In the Financial category there are also several barriers that could be addressed through the implementations of Digital Twins. These are as follows:

- Unpredictable financial returns and economic savings
- High cost of eco-friendly materials and products
- Unclear financial business case for CE construction *

Unclear financial returns and economic savings and unclear business cases are potentially solved through the implementation of the material information stored, the predictive capabilities of AI and the resulting financial ecosystem generated through existing parties exchanging and trading materials and services. The sharing of clear and understandable information through for example material platforms could also drive down risk and gather multiple organisations in one place crating competition and lower prices.

In the Management category the following barriers could be impacted through the use of digital twins:

- Lack of standard indicators, systems, and data collection for performance assessment *
- Lack of successful business models and frameworks to implement circular construction projects
- Complex planning requirements and management processes

Digital twins could potentially be used to standardize information of performance assessment. Through them being tuned for specific platforms or through the implementation of a translator app which could translate existing data stored and produced in one twin into different standards depending one use. Furthermore, Digital Twins also could simplify management processes through automation capabilities and simplification of data outputs.

The technological barriers are as to be expected also potentially resolved through the use of different digital twin configurations. Digital Twins are potential capable of resolving the following barriers:

- Lack of technology infrastructure readiness
- Lack of proven technologies and equipment for CE construction
- Lack of robust information systems to track recycled materials
- Lack of enabling digital technologies and solutions
- Limited technology design for end-of-life products

Inherently by the topic of this thesis and other ongoing research into the use of digital twins for circularity in the built environment more pilot programs will be started. The more companies that introduce this and the related technologies the more information becomes available the more its proven, thus more investment and the growth of the larger industry wide infrastructure based on Digital Twins for Circularity in the Built Environment. Digital Twins provide a solution to the track and trace barrier, whilst predictive capabilities facilitate the capacity to design for end of life of products. By providing certain subcomponents mentioned earlier, such as marketplaces and the translator app, the organic growth of infrastructure could be modularly facilitated.

Supply chain barriers are also potentially addressed through the use of Digital twins. The barriers that are addressed from this category are:

- Fragmentation and complexity of the CE supply chain network in construction *
- Lack of collaboration and communication among stakeholders in the supply chain *
- Lack of standardized processes and certifications for recycled materials *
- Difficulty in tracking and verifying the origin and quality of recycled materials
- Challenges in reverse logistics and product take-back systems *

Fragmentation and complexity could be addressed through the fact that twins are meant to act as repositories of information. This information would make clear of what materials are present in buildings, how the need to be disassembled or reclaimed, their state currently and potentially I in the future and how long they will still be usable. The fact that the data will be available will facilitate create the possibility to share information's. Through translation apps and platforms this could be shared between organisations facilitate collaborations. Standardization could be automated on the back end through AI and different certifications on a material level could be requested automatically via platforms. Tracking and verification of origins could also be checked through the material passports and reverse- logistics could be handled by intermediaries and Circular Material brokers.

Lastly Environmental barriers are also partially addressed through the use of Digital Twins. The barriers addressed are as follows:

- Limited availability of environmentally friendly construction materials and technologies
- Lack of environmental assessment tools and standards for circular construction

As stated earlier by implementing digital twins less materials will be wasted as their life will be extended past the end of a building's life cycle. Additionally predictive algorithms could assess the state and future state of materials and based of standards set in the real world could be automatically assess compliance. This could remove short term need for standardization and allow the ecosystem to grow and international regulatory standardisation to potentially catch up.

4.3.7 Obstacles for Digital Twin Implementations

As seen in the previous chapter Digital Twin have the potential to address several of the potential barriers to circularity. However Digital Twins are themselves subject to several barriers that could prevent organizations of implementing Digital Twins for Circularity. In This chapter we will briefly discuss several of these obstacles. It should be noted that these will be discussed in a generic manner as to facilitate analysis of barriers and challenges provided by the interviewees.

Safeguarding of data and the issue of ownership.

The issue of cybersecurity is of significant importance, particularly in online contexts. The exposure of sensitive data, such as private information, poses a significant and noteworthy risk (Adams, 2019). This danger is particularly pronounced in initiatives that prioritise security, such as those involving government-owned assets or the implementation of digital twins at the municipal level. The challenges of data privacy and ownership, which need the establishment of access levels and permissions, are significant and prominent concerns within the realm of digital twins (Shao & Helu, 2020). The resolution of intellectual property rights and legal concerns pertaining to digital twins necessitates the establishment of designated roles and duties, as well as the delineation of data accessing constraints for all involved parties (Adams, 2019). According to CDBB (2019), although security and ownership concerns are expected to significantly influence the adoption of digital twin technology, they are not anticipated to substantially impede the progress of digital twin advancement. The National Digital Twin programme initiated by CDBB aims to promote the creation of digital twins by offering guiding concepts and supportive tools to organisations. These resources assist organisations in effectively using, updating, and adapting digital twins throughout their process of development and deployment. The security principle of the CDBB necessitates that digital twins be designed with security in mind. This design approach is crucial for safeguarding personal data and privacy, protecting sensitive national infrastructure assets, preserving commercial interests and intellectual property, and mitigating risks associated with data aggregation. The Gemini principles, as outlined by CDBB (2019), seek to build a fundamental framework for realising the overarching objective of developing an interconnected network of digital twins.

Lack of standardised data standards and tools

The establishment of standardised data protocols and the ability for systems to seamlessly communicate with each other are crucial factors that facilitate the development and acceptance of digital twin technology. The absence of agreement about standards, methods, and processes poses a difficulty to the establishment of digital twins (Rasheed et al., 2020). The aforementioned concern is likewise intrinsic to the facilitating technologies of a digital twin. One significant challenge in establishing a complete and operational common data environment (CDE) is the hindrance posed by data exchange and the interoperability of digital models (CDBB, 2019). The use of open standards is crucial in guaranteeing that the advancement of digital twin technology remains independent of specific vendors (Qi & Tao, 2018). The essential implementation of digital twin operations necessitates the supply of job-specific technologies that facilitate the storage, access, and modification of information. According to Qi et al. (2018) and Lu et al. (2019), the primary reason for the inadequacy of current tools in effectively integrating the necessary components for digital twin applications is the presence of diverse standards, formats, and protocols. Re Cecconi et al. (2017) identified the lack of standardised protocols as an additional obstacle impeding the successful integration of digital twins in facility management. Therefore, it seems that there is a general agreement about the need of establishing shared operational norms and resources to streamline the creation and execution of digital replicas in the constructed milieu.

Diversity within source systems.

The incorporation of diverse models with distinct parametric values, spatial values, and temporal scales into the digital twin continues to pose a significant problem (Schleich et al., 2017). The aforementioned factor poses a challenge to the capacity of generating virtual models that provide an accurate and unbiased depiction of tangible resources (Grieves, 2016). According to Qi et al. (2018), the conventional databases are insufficient in handling the growing variety and amount of digital twin data obtained from various sources. Furthermore, the task of harmonizing the disparities in both the meaning and structure of data is an additional obstacle (Lu et al., 2020). Hence, it is important to establish a consensus about the utilisation of comparable instruments and the implementation of a complete database system to facilitate the effective exchange and management of information (Qi & Tao, 2018). It is noteworthy that the obstacles encountered in the creation and implementation of digital twins, as indicated by the existing body of research, seem to bear resemblance to the hurdles encountered in the adoption of Building Information Modelling (BIM) practises within the Architecture, Engineering, Construction, and Operations (AECO) business. In further investigations, it is recommended to conduct a more comprehensive examination of these difficulties by using a systematic categorization approach. This might include organising them into several categories, including technology-related challenges, process-related challenges, policy-related challenges, and people-related challenges (Hong et al., 2019; CDBB, 2019).

Cetin et. Al presented additional barriers however this was an analysis of a different definition of digital twins and considered the each of the previously mentioned edge technologies as individual element. This means that the barriers individually apply to a sub part of the differing Architypes of digital twins. Noteworthy is that this research also considers the implications of the use of implementing circular strategies.

Financial and Economic challenges

Cetin et. Al (2022) highlighted that as stated above the issues of lack of standardization and diversity of sources is a key element of creating issues when it comes to implementing technologies such as digital twins and their sub-components. It according to the interviewees technologies only adds financial strain on organisations trying to implement digital, such as material passports. It stresses both financial and human capacity of organisations.

Furthermore, Cetin et. al (2022) Highlighted that when it comes to the implementation of technologies the lack of market parties with the capability to digitize a physical asset, especially in larger quantities is a significant barrier. Certain methos for the implementations such as manual data entry are not a viable option according to the interviewees.

Additionally, it should be stated that the investment required of these technologies makes it an unattractive prospect as it is a large investment that might only pay diffident in the future. This is financial hesitancy is further exacerbated by the lack of clearly defined business models for implementing technologies to address circularity goals.

Additionally, when considering cross company exchanges of materials there is a lack of material stock amounts to create a proper supply and demand chain for materials.

Cultural challenges

During the interviews conducted by Cetin et al. (2022), the cultural challenges of implementing of digital technologies were also highlighted. These stemmed from a reluctance to use technologies on a regular basis. The interviewees indicated a preference for using rudimentary methos instead of overly complicated technology, furthermore, there seemed to be a preference for old methods even when new tools were introduced. This preference would lead to some members of organizations to keep using the methods they were used to. This pertained especially to 3D representation of buildings.

Cetina et al. (2022), further highlighted that the building industry is a slow one when it comes to the adoption of technologies, as it is just a slow industry in general.

Regulatory Challenges

When considering the regulatory implications of digital twins and their associated technologies, Cetin et al (2022), highlights an issue discussed in a previous chapter. Material standards and assessment are neither well defined enough or universal enough to be applied broadly. This is a challenge related to circularity, however the issue for Digital twins that interface with marketplaces stems from a lack of information and what particular information is needed. Different types of companies and different type of strategies might all require different information especially when considering cross border trade of materials.

Furthermore, according to cetin et al. (2022) even the method and degree of evaluation of materials for circular strategies is a challenge, as non-have been agreed upon and accepted enough. Again, this is a circularity barrier which also generates issues for the adaptations of technologies. Hampering the use of digital twins and associated technologies to display or assess data as standards have not been agreed upon. This could hinder the material passports which certain digital twins might rely upon and marketplaces that would be inconsistent depending on which ones an organisation may consider. This relates to the standardisation challenges mentioned above but is its own unique challenge as it implies that laws and rules cannot be created due to the lack universally agreed upon requirements.

4.4 Conclusion

In summary, the exploration of the Built Environment (BE) has revealed its dynamic nature and multifaceted components. The definition provided by Bartuka (2007) forms the foundational framework for this thesis, emphasizing the human-centric purpose of structures, their impact on the environment, and their influence on human interaction. Aligning with circular economy principles, the BE is viewed through a lens that incorporates ecological and environmental considerations.

The BE, as dissected by Batruska (2007), encompasses various interconnected components, including products, interiors, structures, landscapes, cities, regions, and the earth. For the purposes of this study, a focused approach excludes cities, regions, and the earth. Moreover, as the study delves into the implementation of Circular Economy and Digital Twins, an emphasis is placed on key sectors—Urban Planning, Property, Construction, and Design—each with its distinct roles and stakeholders.

Examining the literature, it is evident that achieving a shared understanding of the BE remains a challenge, with diverse perspectives emphasizing different elements, from buildings to socio-ecological systems. Stakeholders, identified by Koukopoulou (2020), play pivotal roles across the circular built environment, spanning ownership and planning, design and construction, to the supply chain and recovery specialists.

Transitioning to the Dutch context, the construction sector's resilience post-2007 economic downturn is noteworthy. Government initiatives, such as the Circular Economy concept, have propelled growth, with a positive outlook for the future. Despite the challenges posed by the COVID-19 pandemic, the Dutch government has implemented financial aid schemes, supported infrastructure projects, and embraced digitalization, positioning the country as an innovative force.

Analysing the phases of the linear built environment life cycle, from change initiation to renewal and recovery, provides a structured understanding of its evolution. Different sectors and professionals contribute at each stage, underscoring the collaborative and cyclical nature of the BE.

As stated in the literature review the concept of circularity in the built environment is a multifaceted and evolving paradigm that addresses the environmental and social challenges posed by the construction and operation of buildings and infrastructure. The reviewed literature provides a comprehensive overview of circularity, emphasizing key principles such as closed-loop systems, resource efficiency, waste reduction, and regenerative design. The definitions presented by various authors highlight the diversity of perspectives on circularity, ranging from closed-loop material cycles to the promotion of renewable resources and the consideration of the entire life cycle of buildings and infrastructure. The identified clusters of definitions further contribute to a nuanced understanding of circularity in terms of closed-loop systems and efficient resource use, renewable resources and positive environmental impact, and design for lifecycle, resource retention, and waste minimization.

As the built environment faces increasing environmental and social challenges, the adoption of circular economy principles emerges as a promising strategy to create a more sustainable and resilient system. The integration of circularity strategies, as discussed in the subsequent section, provides a framework for implementing circular practices across the various stages of the building life cycle. These strategies encompass regeneration, narrowing resource loops, slowing resource flows, closing resource loops, and collaboration within the construction supply chain. As circularity continues to gain momentum, it is imperative for practitioners and researchers to align their efforts and contribute to the transition towards a circular built environment. This holistic approach holds the potential to optimize resource use, minimize waste, and foster innovation, thereby promoting a more sustainable and regenerative built environment for the benefit of both present and future generations.

The identified strategies—Regenerate, Narrow, Slow, and Close—offer a holistic approach to addressing resource flows throughout the entire life cycle of buildings. The work builds upon the categorization proposed by Bocken et al. (2020) and introduces the strategy of "Collaborate" to address supply chain inefficiencies in the construction sector.

The Regenerate strategy emphasizes the use of renewable and non-toxic materials, powered by renewable energy, aligning with the biological and technical cycles of the circular economy. Examples include the incorporation of renewable materials, self-charging products, and the contribution to regenerating polluted ecosystems. The strategies proposed for Regenerate involve fostering human-nature co-habitation, avoiding hazardous building products, improving indoor and outdoor environments, and exchanging excess resources.

The Narrow strategy focuses on resource efficiency and product input reduction, with an emphasis on designing products with low-impact inputs and incentivizing users to consume less. Strategies for Narrow include designing with reused materials, optimizing lightweight structures, and maximizing the use capacity of products through sharing.

The Slow strategy aims to extend the valuable service life of products and materials, with principles such as design for physical durability, lifetime extension, and smart use of space. Slow strategies involve designing for long life, reversibility, and reuse, as well as providing products as services to minimize resource intensity over time.

The Close strategy focuses on bringing post-consumer waste back into the economic cycle, with principles like designing for primary recycling, enabling product returns, and organizing local waste-to-product ecosystems. Strategies for Close include recycling, urban mining, industrial symbiosis, and tracking and tracing resources throughout the lifetime of buildings.

Additionally, the role of technology as a supporting strategy is highlighted, emphasizing the importance of information technology in facilitating circular economy practices. The Circularity Matrix presented in the chapter further enhances the understanding of how these strategies can be implemented across different phases of the built environment life cycle, from pre-build to end-of-life.

In summary, this chapter not only categorizes and explains circularity strategies but also provides practical examples and proposed strategies for implementation in each phase of the built environment life cycle. The Circularity Matrix serves as a valuable tool for understanding the alignment of these strategies with specific phases, contributing to a more nuanced and targeted approach to circularity in the construction industry.

The systematic review of barriers to circular economy adoption in the construction industry highlights the multifaceted challenges hindering the industry's transition. The identified categories of barriers, including economic/financial, technical, cultural, social, environmental, informational, institutional, political, and technological barriers, provide a comprehensive understanding of the impediments. Notably, economic/financial barriers, such as high upfront costs and limited market demand for recycled materials, emerge as prominent challenges, emphasizing the need for financial incentives and supportive economic frameworks. Concurrently, technical barriers, encompassing issues related to design codes and technological infrastructure, underscore the importance of fostering innovation and technological advancements for circular practices.

While addressing economic/financial and technical barriers is crucial, it is essential to recognize the interconnected nature of these challenges with other categories. Cultural and social barriers necessitate concerted efforts to shift perceptions and raise awareness, making recycled materials more socially accepted. Regulatory and institutional barriers demand the development of robust policies and support frameworks, ensuring a conducive environment for circular practices. Environmental considerations, informational gaps, and political challenges also warrant attention to create a holistic approach to circular economy adoption in the construction sector.

The last Chapter discussed the technology which is one of the main subjects of this paper namely Digital Twins.

In conclusion, digital twin technology has emerged as a transformative force in the construction sector, holding immense potential to enhance project management, safety, and facility management. The concept involves creating a virtual replica of a physical asset, allowing for diverse applications throughout its lifecycle. The advantages offered by digital twins, such as improved safety, collaboration, and efficiency, are particularly valuable in construction processes. Stakeholders benefit from the ability to visualize and simulate various scenarios, identify potential issues, and optimize design and construction procedures. Beyond construction, digital twins extend into facility management, offering real-time data access, performance monitoring, and informed decision-making for building owners and facility managers. Originating from aeronautical engineering and cyber-physical systems, digital twins have transcended industry boundaries, finding applications in manufacturing and smart cities. Integration with technologies like the Internet of Things (IoT) and artificial intelligence (AI) further amplifies their capabilities. Despite their broad utility, the term "digital twin" lacks a universally agreed-upon definition, reflecting its evolving and contextual nature. As the technology matures, it is poised to continue transforming the construction sector and beyond, with applications projected to expand across various disciplines. The ongoing research on different iterations and functionalities of digital twins underscores the need for further exploration and standardization in this dynamic and promising field

The chapter discussing Digital Twin Archetypes begins with exploring the various dimensions and meta-dimensions that contribute to the classification of different digital twin typologies. The categorization, based on factors derived from both literature review and expert insights, includes dimensions such as data collection, data handling and distribution, and conceptual scope. The meta-dimension of data collection encompasses processes like data acquisition, source, synchronization, and input, with automated data acquisition identified as mandatory. Data handling and distribution meta-dimension covers data governance, data link, interface, interoperability, and purpose, emphasizing the critical role of data governance and the importance of bi-directional data links. The conceptual scope meta-dimension includes accuracy, conceptual elements, and time of creation, highlighting the significance of accuracy in representing physical assets and the relationship between the physical and digital elements.

The discussion then transitions to digital twin archetypes, classifying them based on their characteristics and capabilities. Archetypes range from basic representations with a human-machine interface to exhaustive digital twins that integrate multiple edge technologies. These edge technologies, including BIM, cloud computing, 3D scanning, IoT, AI, and digital material platforms, play crucial roles in enhancing the functionalities of digital twins.

Furthermore, the integration of these edge technologies within different archetypes is explored, illustrating how each archetype leverages specific technologies to fulfil its purpose. The exhaustive digital twin archetype, in particular, stands out for its comprehensive integration of edge technologies and its potential to create a network of interconnected digital twins.

Finally, the chapter emphasizes the need for interoperability and data sharing among digital twins, digital platforms, and humans, introducing the concept of a translator application or tool to facilitate seamless communication by adjusting data sets according to different standards. Overall, the exploration of these dimensions, archetypes, and edge technologies provides valuable insights into the diverse landscape of digital twins in built environments.

The exploration of potential configurations by the author of digital twins and their connection to various circularity strategies throughout the different phases of the building life cycle created a hypothetical integration of AT into the circularity matrix. This can be used as to test the configurations by the potential interviewees. The discussion has centred on the distinct capabilities of each digital twin archetype and how they align with specific circularity strategies. For the slow strategy, Archetype 1 plays a crucial role in facilitating design-focused activities, storage of raw data, and predicting the state of materials, particularly in e use and end-of-life phases. The narrowing strategy relies on Archetypes 2 and 5, emphasizing resource efficiency, localizing supply, and predicting material states to minimize waste during the construction and end-of-life phases. The close strategy involves Archetypes 3 and 5, focusing on design, accessing information about material sources, and enabling recycling resources in the prebuilt and end-of-use phases. Lastly, the regeneration strategy involves Archetypes 1, 2, 3, and 5, with a particular emphasis on their analytical and predictive capabilities for ecosystem management and sustainable construction practices. These insights underscore the importance of selecting the appropriate digital twin archetype for specific circularity strategies in different phases of the building life cycle, contributing to more sustainable and efficient built environments.

The implementation of Digital Twins in the context of circularity strategies faces several noteworthy barriers that organizations need to address for successful adoption. One prominent challenge revolves around the safeguarding of data and issues of ownership, where cybersecurity concerns, data privacy, and ownership disputes emerge as significant hurdles. The need for secure digital twin environments necessitates careful consideration of access levels, permissions, and resolution of intellectual property rights. Another substantial barrier is the lack of standardized data standards and tools, posing challenges to interoperability and hindering the development of a common data environment. The absence of agreed-upon standards, methods, and processes complicates data exchange and integration of diverse digital twin components. Furthermore, the diversity within source systems, encompassing variations in parametric values, spatial values, and temporal scales, presents a significant challenge, requiring consensus on the utilization of comparable instruments and a comprehensive database system. Finally, financial and economic challenges, as highlighted by Cetin et al. (2022), underscore the strain on organizational resources and the lack of market parties capable of digitizing physical assets at scale. Cultural challenges, reflecting a reluctance to adopt new technologies and a preference for traditional methods, also contribute to barriers in the implementation of Digital Twins. Regulatory challenges compound the situation, as material standards and assessment criteria lack universality, hindering the broad application of digital twins in the context of circularity. Addressing these barriers will be crucial for organizations aiming to leverage the potential of Digital Twins for circularity in the built environment.

Thus, in conclusion it can be stated that the built environment the holistic view of the built environment encompasses many domains, however a building centred definition is used in this paper. Circularity as stated is a growing occurrence in the Built environment and there were several identified barriers including economic/financial, technical, cultural, social, environmental, informational, institutional, political, and technological barriers to the implementation of circularity. Each of these had its own variations. Furthermore, there are four circularity strategy categories available again each encompassing various sub strategies. Based on the phases discussed of the building's life cycle a matrix was created and populated with each of the sub strategies.

Digital twins as tool were discussed, defined and categorized. The capabilities of each category of digital twins (Architypes) were established and potentially needed edge technologies were discussed. This was then used to create a possible configuration of Digital Twins and corresponding circularity strategies. Furthermore, potential barrier to digital twins were again discussed.

Thus, this literature review creates a case for the use of digital twins as possible enablers of circularity on the level of buildings and lays out the potential barriers to each both circularity and digital twin implementations separately. This allows for an analysis of expected and experienced barriers for the implementation of digital twin as a tool for circularity by a variety of actors.

5.0 Results – Empirical Research

5.1 Interviewee description

The selected interviewees, as stated before the interviewees were selected based on if they partook in the Dutch circular built economy. They were selected from across the supply chain, and they carry out a variety of activities and employ a divers set of circular strategies. For this thesis 13 companies interviewed Ranging from design and advisors to the builders and recyclers.

Below is an overview of each of the interviewees their organization description their circular activities

Interview Number	Interviewee Position	Document & Location
1	Project developer & director	This interview was conducted at the real estate (re)development branch of a large architectural firm. They specialize in the (re)development of residential, commercial, office, and leisure projects. They operate both as risk-bearing developers and delegated developers, always prioritizing quality, circularity, and commercially viable sustainability concepts. Their services extend to a comprehensive suite of management and advisory services in building and area development.
2	Head of Research Unit	A technology development firm for construction and engineering companies that headquartered in the Netherlands, it operates in various sectors of the construction industry, including civil engineering, building construction, property development, and infrastructure projects. The interviewee works in a department related to digital innovation. The firm provides software, consultancy and research services.
3	Program Manager of the Digital Construction	A very large construction company with a focus on sustainability and innovation. The interviewee is actively involved in the company's efforts to implement digital twin technologies within the organization. They discuss the company's commitment to sustainability and its desire to leverage digital twins to enhance its construction practices. The interviewee's role within the company is not explicitly stated in the provided excerpts. However, based on their discussions about the company's sustainability goals, digital twin initiatives, and involvement in driving change management and data management strategies, it can be inferred that they hold a position of influence within the company, possibly in a leadership or managerial capacity related to innovation, sustainability, or technology implementation.
4	Team Leader of Circular Team	The company is an engineering firm specializing in circularity, particularly in the reuse and repurposing of materials. The company is depicted as actively involved in various aspects of the circular economy, such as material inventory, database management, and facilitating material reuse for clients. The company are facilitator, bridging the gap between material suppliers, contractors, and clients to optimize material flows and promote sustainability in construction projects. Their approach is characterized by a neutral stance towards material outcomes, prioritizing environmental considerations and promoting circular strategies across different project phases.
5	Lead interior Design Team Associate Director	This Interview was conducted at a large international firm. Their Dutch branch has a department that focusses on interiors. This here an interview was conducted. They function as an interior design firm that specializes in creating interior spaces for various projects. Their activities involve designing interior spaces, calculating costs, and considering sustainability factors such as Life Cycle Analysis (LCA) to support circularity strategies.
6	Product Manager	The interviewed company offers a digital platform for managing material passports, promoting sustainability in construction through consulting and advisory business practices. It facilitates tracking materials throughout building lifecycles, aiding transparency and efficient resource use. Integrated with BIM systems, it enables sustainability assessment and informed material choices. The

		company advocates circular business models like product-as-a-service, promoting material reuse. Challenges include data security and competition concerns, which are addressed through secure storage and selective data sharing. Overall, it's a forward-thinking entity advancing sustainability and circularity in construction and real estate sectors through digital innovations and collaborative initiatives.
7	Building Physics and Sustainability Consultant, Unit Manager	The company is a leading advisory firm, focusing on building physics, acoustics, and sustainability. It specializes in optimizing the environmental performance of buildings through advanced material selection and design strategies. They work on new construction projects and renovations, employing technologies. they are committed to circular economy principles.
8	Operations Director	The company's focusses on modular wood construction to support the transition to circular building. The company developed a module to facilitate this shift.
9	Program Manager, Sustainability Program Manager	A major construction firm in the Netherlands, focused on sustainability and innovation. It is dedicated to reducing the environmental impact of construction through sustainable material use and circular construction practices. The company has shifted from consulting to actively implementing sustainability strategies in its projects, aiming to make a significant impact by being directly involved in the material lifecycle. The interviewee works within the infrastructure subsection but has a holistic involvement with digitalization across the company.
10	Researcher in Reliable Structures Department	The organization is described as a research institution focused on applied scientific research. It conducts studies on various aspects of circularity and construction, particularly in infrastructure. The organization is involved in projects aimed at extending the lifespan of existing structures, such as bridges, and promoting sustainable steel production. Additionally, it collaborates with other departments on projects related to sustainable transportation methods. Overall, it plays a role in advancing sustainability and circularity across different sectors through research, advisory and consulting activities.
11	Owner and Director	This interview was with the owner director of two companies in the Dutch Circular Built Environment. The first is an architectural firm with a vision for a sustainable future where individuals from all walks of life can live, work, and play in a healthy and safe environment. The second is an ambitious hybrid living concept for the modern sustainable city based in the Netherlands
12	Senior Sustainability Advisor	a consultancy and advisory firm specializing in sustainability and environmental aspects, particularly in the context of buildings and construction. They provide services such as advising clients on policy and implementation to make buildings more sustainable, developing methodologies for assessing environmental performance, and offering software applications
13	Sustainable Business Developer and /Member of Commercial and R&D Team	The company specializes in the production of three-story houses entirely within their factory, utilizing cross-laminated timber (CLT) as the primary building material. They manufacture fully equipped homes, including kitchens, bathrooms, and installations, within the factory. These homes are streamlining the building process.

Table 5: Interviewee description

5.2 Position in the matrix

To facilitate the discussion with the interviewees each of them was asked after presenting them with an explanation of the circularity matrix to place themselves within it. This in order to create a common taxonomy between the interviewee and interviewer.

Interviewee1:

Stated that in their multifaceted approach to sustainable construction, they engage with various strategies, predominantly focusing on the **slow loop, narrow loop, and regeneration**. Although initially considered, the close loop strategy was abandoned due to its tendency towards downcycling. Their involvement spans all project phases, from initiation and financing to design and construction, through their integrated architect's office. They not only design and build but also deconstruct and reuse materials from existing structures, ensuring a holistic approach to sustainability. Additionally, our operations sometimes extend to maintaining the projects, thus maintaining control over the **entire building lifecycle**. They emphasize the use of bio-based materials and the necessity of designing for reusability to support sustainable practices.

Interviewee 2:

The interviewee stated that the company is not strictly aligned with specific circularity strategies, but rather on providing holistic solutions tailored to client needs across **various phases** of the building lifecycle. The company works extensively with standards, such as those related to inspection, but there aren't specific strategies delineated within the company. They prioritize interoperability and adherence to standards like IFC for data exchange.

Their work encompasses different phases of the building lifecycle, including **design**, **construction**, **maintenance**, and considerations. For instance, they are involved in developing technologies that facilitate decision-making during the construction phase, such as enriching Building Information Modeling (BIM) with real-time data from suppliers to enhance project accuracy. Additionally, they focus on extending the lifecycle of products or buildings, emphasizing strategies like predictive maintenance to prolong product/component lifetimes and exploring possibilities for reuse or repair before eventual disposal.

Their approach is more about providing adaptable solutions that can address various circularity challenges across different phases of a building's lifecycle rather than being constrained to specific strategies or phases. This adaptability allows them to cater to the diverse needs of their clients and the complexities of circularity within the built environment.

Interviewee 3:

The interviewee stated that the company is a large organisation, with a focus on **Pre-Build** and **Construction**

.

The company's approach to circularity encompasses a multifaceted strategy embedded within its overarching vision of sustainable construction. The program manager for digital construction elucidates the company's commitment to reducing environmental impact through the adoption of sustainable materials like eco-friendly concrete and asphalt blends. Despite regulatory and quality assurance challenges hindering the implementation of biobased and low carbon materials, the company persists in its pursuit of eco-conscious solutions. Integral to this strategy is the emphasis on sustainable growth, selecting projects aligned with sustainability objectives. While the company primarily operates within the design and construction phases, where material choices wield the most significant influence, its circularity initiatives extend across the **various domains.** In the prebuild phase they actively stated that they used **narrow** and **regenerate** strategies focused on materials and components that are selected. But their focus on strategies is based according to the interviewee active over **all strategies** based on the needs of the specific projects and clients. But the activities they undertake usually fall into the **prebuild** and construction phase.

Interviewee 4:

The company primarily focuses on circularity strategies related to inventorying existing materials, streamlining material chains, and facilitating material reuse and repurposing. They are actively involved in the **demolition** phase, as evident from their emphasis on recording the inventory of materials from existing buildings. Their approach involves cataloguing various properties of these materials into a database, enabling them to offer products to other parties and potentially diverting them from landfills. Additionally, they aim to **close** material loops by coordinating with contractors to refurbish or repurpose materials, thereby reducing waste and promoting circularity. Furthermore, the company assists organizations in creating material passports and preserving BIM models for future reference, indicating their involvement in documenting and managing **materials throughout their lifecycle**. While they are not directly engaged in construction activities, their efforts in material inventorying, reuse, and documentation contribute significantly to promoting circularity within the end of life phase. However, depending on the request from the request from the client they **could be active during all Phases**. And the interviewee also stated that the company focus mostly on **regeneration** strategies. They interviewee stated they consider themselves as the spiders in the web, and therefore they stated they could be active in the design phase by bringing in a firm to add their design capabilities to them, or by bringing in builders to help them execute plans. They have a specific focus on gathering information for the end of life phase but the state that they are active according to the needs of their clients.

Interviewee 5:

The interior branch of this large company was stated to be employing circular strategies. The company is focusing on several circularity strategies aimed at **different phases** of the building lifecycle. They emphasize **design** principles that facilitate easy disassembly, recycling, and flexibility, thereby **extending the lifespan** of building elements. Additionally, they prioritize the use of biobased materials and aim to create positive ecological impacts. These strategies align with circular principles of **maximizing material longevity, minimizing waste, and promoting sustainability**. They are actively engaged in the **pre-build phase**, particularly during the design stage, where they integrate these circular principles into the building's conceptualization. Moreover, they recognize the importance of considering the **entire lifecycle** of a building, including the specifically the **use phase**, where they aim to complete the circular loop by implementing strategies that promote material reuse and sustainability. Overall, their approach encompasses circularity throughout the building lifecycle, however from the perspective of the building as a structure they focus on the use phase. Within this perspective they are active , from pre-build to construction and use, emphasizing design for longevity, flexibility, and ecological benefit.

Interviewee 6:

The company is primarily active in **the pre-build phase** of the building lifecycle, although their platform can be **utilized across all phases**. Their main focus lies in providing tools for assessing and improving the sustainability of building materials, which aligns with circularity strategies such as **"Close**" and **"Regenerate**." They offer a platform, where construction companies, real estate owners, and other stakeholders can upload BIM files or Excel sheets to map the material intensity of buildings and assess environmental impacts, including CO2 emissions. This process enables users to evaluate the sustainability of their building materials and make more informed choices during the pre-build phase, potentially improving reuse potential and increasing recycling rates. Additionally, they offer a material passport feature, serving as a digital twin environment where users can track materials and record adjustments throughout the building's lifecycle. The company's platform also integrates with other software systems through API connections, streamlining data transfer and facilitating real-time updates. While their focus is primarily on providing tools and insights rather than dictating specific strategies, their offerings support circularity efforts by enabling users to make more sustainable material choices and improve the overall environmental performance of their buildings.

Interviewee 7:

According to the interviewee the companies employ a combination of circularity strategies, including "Close" and "Regenerate," with a possible inclusion of "Narrow. The focus lies on facilitating material reuse and recycling, primarily during the pre-build phase, aiding users in sustainable material choices and enhancing material reuse potential. The "Regenerate" strategy underscores designing for easy disassembly, recycling, and flexibility, predominantly utilized in the pre-build phase to evaluate and enhance the environmental performance of materials. While not explicitly mentioned, the companies may also employ a "Narrow" strategy, concentrating on specific aspects of circularity across phases, particularly during pre-build and construction, ensuring sustainable practices are integrated into design and construction processes. Overall, the companies' circularity strategies primarily impact the pre-build phase, providing tools and insights for sustainable material choices and design decisions, with implications for other lifecycle phases, including construction, use, and potentially end-of-life, to promote material reuse, recycling, and environmental responsibility. This advisory firm does not appear to have specific activities in the construction phase and in the end of life phase interviewee did state that they are active in assessing what's left and what could be done with components and materials.

Interviewee 8:

According to the interviewee the company employs various circularity strategies, focusing primarily on "**Slow**" and "**Regenerate**," while also incorporating aspects of "**Close**."

In regard to Regenerate their core strategy involves using materials that the earth can regenerate within the lifespan of the building, particularly emphasizing biobased materials. This approach not only supports sustainability but also aids in CO_2 capture. This strategy is active in the pre-build phase, where they prioritize selecting sustainable, regenerable materials. They also consider their strategies part of this category as they use the materials in such a way that the materials have a chance to regenerate in the natural ecosystem.

In terms of Slow strategies their aim is to maximize the lifespan of materials and modules by designing buildings that are highly durable and adaptable. This involves creating structures that can be easily disassembled and reused, ensuring that materials remain in the economic value chain for as long as possible. This strategy spans across the **pre-build, construction,** and **use phases**. In the pre-build phase, they focus on design for durability; in the construction phase, they implement modular and dry construction methods; and in the use phase, they ensure ease of maintenance and adaptability.

Although they are not actively involved in the end-of-life phase, their design facilitates this process. The strategy is evident in the end-of-life phase, where the modular and easily disassemble nature of their buildings allows for efficient material recovery and recycling.

Overall, according to the interviewee, the circularity strategies are deeply integrated into the pre-build and construction phases, with provisions that extend their impact into the use and end-of-life phases through design features that support material longevity, adaptability, and recyclability.

Interviewee 9:

According to the interviewee the company employs various circularity strategies throughout different phases of the building lifecycle. For **Narrow** they focus on reducing material use by making buildings lighter and more efficient, an approach that is particularly evident in the **pre-build** and **construction** phases. This strategy involves using innovative materials like steel or composites instead of traditional, heavier materials like concrete. They employ **Slow** by designing buildings that are easily demountable and adaptable, they ensure that the lifespan of the materials and structures is extended. This strategy is active in the **pre-build, construction**, and **use** phases. They create modular designs and use materials that can be reused or repurposed, thus slowing down the material lifecycle. When regarding **Close** the company emphasizes recycling and reusing materials, particularly in the **end-of-life phase.** They collaborate with suppliers early in the **design phase** to ensure that materials can be efficiently reclaimed and recycled, **closing** the loop on material use. In regard to **Regeneration** the company is active in residential projects, where they focus on using biobased materials, which are more easily renewable. This strategy is prominent in the **pre-build** phase, where they select materials like wood, biobased insulation, and interior walls made from renewable sources. They also support the growth of such materials, like flax and hemp, on their properties.

Overall, the company is active in all phases of the building lifecycle—pre-build, construction, use, and end-of-life—with a tailored emphasis depending on the type of construction (residential vs. utilitarian). They aim to be innovative and sustainable, aligning their practices with broader industry goals and ecological standards.

Interviewee 10:

According to the interviewee the function of the company as a provider of technology and as an advisor means they are active across most phases and all strategies. The interviewee additionally mentioned several strategies specifically. In regard to **Slow the strategy is active in the use and end-of-life phases.** The organization conducts reassessments of existing infrastructures, such as bridges, to extend their lifespan and delay the need for new constructions. This involves monitoring and evaluating the current load and structural integrity, which aids in maintaining and repairing structures efficiently. When considering **Close the company, it is mainly employed during the pre-build and end-of-life phases**, the organization is working on producing more sustainable steel by increasing the proportion of recycled steel in the production mix and helping clients acquire and use it. They also focus on establishing regulations and standards to safely reuse steel from decommissioned structures, ensuring that this recycled material can meet the necessary safety and quality standards. **The Regenerate is part of their research on sustainable material production**. For instance, the development of more sustainable methods for steel production, which falls into the pre-build phase, aims to create materials with better environmental credentials that can be used in future construction projects. As stated, the by the interviewee the organization is active across most of the life cycle dependent on the needs of a project or client, however the construction phase was not specifically named, however their sustainable transport services appear focus on lessening the impact transport.

While not directly involved in the design and construction of buildings, the organization's research supports broader circularity goals by providing insights and developing technologies that can be applied across various phases of construction projects. This includes evaluating the life cycle of materials and advising on sustainable practices, thereby contributing to the overall reduction of material waste and promoting a more circular economy in construction.

Interviewee 11:

As stated above the interviewee was the owner and director of a company and in the leadership of a circular housing concept. The firm employs a variety of circularity strategies throughout different phases of the building lifecycle. In the **pre-build phase**, they use strategies such as **narrowing and closing loops** by incorporating materials databases and ensuring the design considers disassembly (losmaakbaarheidsfactor) and material passports. During **construction**, they employ **narrowing and closing strategies** by updating BIM models for execution, ensuring detailed data for procurement, assembly, and installation, which is crucial for efficient resource use. In the **use phase**, they utilize digital twin technology to manage and optimize energy use through IoT integrations, supporting regenerative strategies by enabling real-time monitoring and maintenance, thereby **extending the life of building components**. At the **end of life,** they **apply closing and regenerating** strategies by using the BIM model to manage the disassembly and recycling of materials, leveraging detailed information from the material passports to facilitate recycling and reuse. These integrated approaches ensure the building's lifecycle is managed sustainably and efficiently, catering to client needs and varying project requirements.

They specified that the strategy used is based on the needs of the client as such they are not bound to a set strategy.

Interviewee 12:

As stated above the interviewee works for an advisory firm. They stated to be active in **all phases** in this capacity and to be able to employ **all strategies, however the interviewee clearly stated that their actual activities do not take place during construction, their activities in the pre-build phase impact it but that is the extent of their involvement.** The company employs a comprehensive range of strategies across multiple phases of a building's lifecycle, emphasizing sustainability and circularity. Primarily active in the **pre-build** and **use** phases, they employ "**Slow**" strategies by advising municipalities, housing cooperatives, architects, developers, and investors on policies and practices to enhance the long-term sustainability of buildings. This includes energy efficiency measures and integrated sustainability approaches that consider the material-related CO_2 impact. In the use phase, they adopt "**Close**" strategies, assisting clients with the **maintenance** and **transformation** of existing buildings to facilitate **reuse** and **repurposing** of materials. Their research and methodology development span all phases, aiming to provide a holistic view of environmental impact and sustainability. Although less involved directly in the construction phase, their design recommendations influence this phase to reduce environmental burdens, aligning with "**Narrow**" strategies. Additionally, they promote "**Regenerate**" strategies by advocating for the use of renewable and biobased materials, striving to lower environmental impacts to zero or even positive levels. These combined efforts underscore their commitment to comprehensive sustainability and circular construction practices. They themselves are not active in the construction phase but their activities in the pre-build phase do impact this domain. The interviewee additionally did not mention specific activities in the end of life phase, but they did state to be active in this phase across its own categorization of circularity strategies, which was analogous to the 4 established in this thesis.

Interviewee 13:

The company employs a range of strategies across the different phases of the building lifecycle. During the **Pre-Build** and **Construction** phases, they focus on the **Close** and **Narrow** strategies by using high-quality, biobased materials like CLT wood, which is 93% detachable, facilitating easy disassembly and reuse. They employ screw connections instead of glue, enhancing the removability and recyclability of materials. To further the **Slow** strategy, they ensure longevity and sustainability by securing agreements with suppliers for the return and reuse of wood after 30 years. Additionally, the company minimizes material usage by prefabricating components, which reduces waste and optimizes resource efficiency. For the **End of Life** phase, they implement Close strategies through post-consumer recycling, returning wood fibre composite waste to producers for reuse in new products. During the **Use** phase, the company enhances adaptability and maintenance by designing buildings for easy disassembly and potential upgrades, preparing for future regulatory requirements related to sustainable water use, and using materials that facilitate passive energy management, which extends the building's lifecycle and reduces energy consumption. Overall, their approach encompasses Close, Narrow, Slow, and Regenerate strategies throughout all phases of the building lifecycle, demonstrating a comprehensive commitment to circular construction practices.

Based on these descriptions the interviewees are active in a variety of Phases and always employ a multitude of strategies. Regardless of the organization type i.e. architecture firms, construction companies, advisory firms etc, they work on a variety of methos and are often driven by the needs of the client. Categorizing them is thus a difficult prospect, but this aspect of the thesis has indeed created a common language and understanding of the interviewers perspective on their companies position within the Dutch Circular economy.

The interviewees highlighted diverse approaches to circularity in the building lifecycle, emphasizing different strategies and phases. Interviewee 1 focuses on the slow, narrow, and regeneration loops across all project phases, stressing bio-based materials and reusability. Interviewee 2 provides holistic solutions tailored to client needs without specific strategies, emphasizing interoperability and standards adherence. Interviewee 3 adopts sustainable materials and eco-conscious solutions, primarily in the design and construction phases. Interviewee 4 concentrates on inventorying, reusing, and repurposing materials, mainly during the demolition phase. Interviewee 5, in the interior branch, integrates circular principles in design for longevity and flexibility. Interviewee 6 offers a platform for assessing material sustainability, supporting the close and regenerate strategies. Interviewee 7 combines close, regenerate, and narrow strategies, primarily impacting the pre-build phase. Interviewee 8 employs slow and regenerate strategies, focusing on durable, adaptable designs and biobased materials. Interviewee 9 applies narrow, slow, close, and regenerate strategies across all phases, adapting to project types. Interviewee 10, as a technology provider and advisor, supports various strategies, mainly in pre-build and end-of-life phases. Interviewee 11 integrates multiple strategies throughout the lifecycle, guided by client needs. Lastly, Interviewee 12 advises on sustainability across all phases, promoting slow, close, and regenerate strategies, while Interviewee 13 implements close, narrow, slow, and regenerate strategies with high-quality materials and design for disassembly. Overall, the interviews reflect a commitment to sustainable and circular construction practices, tailored to specific project requirements and client needs.

5.3 Digital Twin Usage

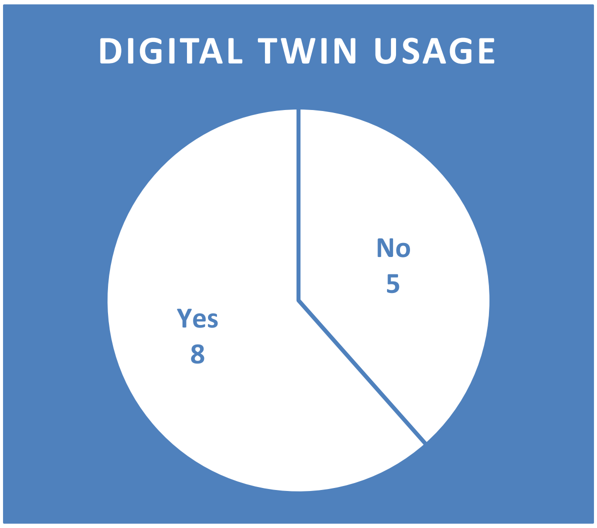

Figure 11: Digital twin usage

In this subchapter we will discuss the respondents and their use of digital twins to support their circularity strategies. It should be noted that more than initially expected use the digital twins as defined in this thesis in support of their employed strategies. In total there were 13 respondents, of which 8 respondents use Digital Twins to support circular activities and 5 did not use digital twins. However, it should be noted that some did employ digital twins but not in support of circular strategies employed by their company. 3 (38%) of them used AT 1 ,2 (25%) of them used AT 2 and 3 (38%) of them used AT3.

As stated above there were 8 respondents who stated that they used digital twins.
AT 1 was used by interviewees 6, 8 and 13.

Interviewee 6 was active in the pre-build phase and provided digital twin technology for circular purposes. They themselves were not involved in the development of the built environment but they provide a technology that can be used specifically for the execution of circular strategies in the built environment. They provide a method in which an existing design can become a comprehensive index of the components and materials in a building, in order for these to be part of a circular ecosystem. So, their digital twin has a specific focus on material passports as a comprehensive repository of information about components and materials, an integrated compatibility with BIM technologies, not only as a 3D model but as an index through which a person can interact with underlying data about components and materials. When it comes to scans and sensors in their definition as input technologies, there is the use of scans as input. It should be noted that the scanning is not necessarily an integrated aspect of their activities, but they consider it a potential input of data to be delivered to the digital twin. Of all the interviewees this on could be considered an outlier, as it's a technology provider for the built environment in general not just circularity. It should be noted that they as providers of a technology (MP'S) don't see themselves as the providers of just the technology, in rudimentary form they share the data across users through a in house platform, thus creating a pseudo digital material platform (DMP).

Interviewee 8 is involved with the circular built environment through the creation of modular residential real estate, created with an emphasis on regeneration as stated in the previous chapter through their use of wood. They make 3 scans of their wooden modules, and they in several pf their modules include sensors to monitor the impact of humidity of on wood in buildings during their use. They also have a standardized BIM protocol and a comprehensive inventory of material and components in each module. The state recorded by the sensors is linked to a specific building component or material in a building but is currently being used for training purposes, either for algorithms or to base their business case upon (what does humidity and exposure duration patterns say about the state of the wood and the larger building in extension of this).

Interviewee 13 is a relatively young company, and yet it has made great strides in developing modular circular housing with the mission to solve the current housing crisis in the Netherlands. They as stated above make fully constructed 3 story residential housing from wood in a factory before transporting it to the site. The interviewee stated that they use BIM to interface with a digital representation of their buildings and they use the rest of the relevant technologies also. They explicitly stated that sensors are used to monitor the moisture conditions to monitor the state of the wood used in the construction. Additionally, they use a Translation Application, namely a platform that translates their models and aggregates it into a network of Digital Twins of real estate in a portfolio.

AT 2 was also used by early adopter. It was used by interviewees 1 and 2.

As stated before interviewee 1 was part of the project arm of a large organisation, developing realestate for their own portfolio or representing a client. They stated that they infuse data into the twin they have making a non-static model, furthermore they use the relevant technologies. They also stated that they see there models as up to date databases that contain comprehensive and accessible data. They use codes and tags to track and identify different components, linking it to their model, facilitating the flow between the building and the model. They stated that they are currently also active in developing more advanced versions.

Interviewee 2 represented a technology orientated company and was the head of their Research and Development department. They themselves as stated before were not directly involved with the real estate but were active as technology providers, with a focus on facilitating decision making throughout a building's circular life cycle. All technologies relevant for the archetypes are present in the Digital Twin technology they provide. Their decision making protocols were also very advanced.

AT 3 was also an archetype used by some of the interviewees. Interviewees 3, 9 and 11 stated that they used the predictive analysis twin as described in this thesis.

Interviewee 3 represented one of the largest companies active in the Dutch built environment. They are active in both real estate development and infrastructure projects. The interviewee stated that they do employ digital twins as defined in this thesis. They used all of the relevant technologies, however it should be stated that they also employ Artificial Intelligence in their decision making processes, however they currently apply this primarily to their infrastructure projects, where it allows for predictive maintenance. They do want to integrate it into real estate in support of their circular activities.

Interviewee 9 was another of the largest active companies in the Dutch built environment. As stated, before they are involved with a diverse set of projects across the matrix. The digital twin they employ, they as stared are currently employing all relevant technologies in a manner that makes it clear they are employing AT 3; however, it should be stated the degree to which they employ digital twins often varies across projects. For example, AI is stated to be used in an experimental phase. A live IOT connection is also in an experimental phase, as stated by the interviewee they do expect to employ it more widely. Despite the infancy of some of the sub technologies the fact they are working with them already justifies putting them with the other early adopters in this group.

The last interviewee categorized to be using AT 3, was interviewee 11. Interviewee 11 was representing two organizations as described above. One was involved with the management of circular real estate and the second was an architecture firm that explicitly stated to focused on developing circular buildings. All relevant technologies were stated to be used; however, the application of predictive AI was stated to be only applied to smaller sub components and not yet the model as a whole.

It is significant to note in the context of this research that the organisations under study did not use Digital Twins that corresponded to Archetypes 4 (AT 4) and 5 (AT 5). These archetypes show more complex and specialised Digital Twin technology configurations that might call for more customisation, integration, or specialised functionalities that weren't in line with the participating organisations' present requirements. Consequently, the study's focus stayed on the difficulties and obstacles related to the more widely used archetypes.

In the following paragraphs we will discuss the Digital Twins that the potential adopters stated best fit the Circular activities they were involved with.

In total 5 of the interviewees stated that they did not yet employ Digital Twins as defined in this thesis to support their circular activities. AT 1 was wanted by two of the interviewees, and AT5 was wanted by three of them. As stated above interviewee 5 is in leadership position within the interior focused arm of a large corporation. The interviewee stated that with their focus on interior redesign and renovations they prolong the building lifespan. The interviewee stated that they do recognize the potential of digital twins enhance their implementations of digital twins. The interviewee stated that they want to use BIM as defined within this thesis, they want it as a tool to access and visual the data. They also stated that they see the potential of scans and sensors during the use phase. Notably the interviewee stated that this simple design and repository twins still needed to be integrated into a wider network via a Digital Material Platform.

Interviewee 10 also stated that they wanted to use AT 1. It should be noted that this was a curios case. As stated, they are a technology focused organization. That advises on and provides technology for actors in the built environment. They do develop and use digital twins; however, they do not use them for circularity purposes. This was stated explicitly. They Digital Twins employed by this organization is quite advanced and does use technologies such as AI. However, to employ it for circularity they would first want to develop and employ a simpler twin. Indirectly it could benefit it, but they would want to develop a more specific model.

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At which is the most advanced and accurate low latency, high fidelity digital twins.

Interviewee 4 was as stated to be an end of life focused company, with a specific focus on the inventory of materials and giving them a second or multiple lives. Through the facilitation of for example circular supply chain by for example sending components back to suppliers for refurbishment and resupplying it to contractors. So, they facilitate the coordination of circular material flows. The interviewee stated that for this work granular data about all components in buildings would benefit their business model. The wish to incorporate some degree of AI to automate the acquisition and analysis of data about buildings, with AI being already able to discern what is best approach with components. Also, with existing buildings without a twin a onetime end of life twin can be created more quickly through automated data acquisition making the end of life material flow easier to implement in a circular way. And a connection to a larger platform could also be beneficial to this organization working method. Interviewee 7 was as stated above an engineering and sustainability consultant active in the pre build and end of life phase. Again, AI is mentioned as a method to speed up and organize data acquisition and as a tool to make prediction and generate strategies. This could as be stated by the interviewee be used in conjunction with a material platform to be part of a larger material ecosystem.

Interviewee 12 is also as state by the interviewee a consultancy firm. They advise clients on integrated sustainability policy creation and implementation. They also evaluate existing buildings on the environmental performance. They are active across the entire lifecycle of the building. The interviewee stated that they are considering digital twins for usage to facilitate their role as consultants. Using AI in conjunction with connections to a wider database to immediately evaluate the sustainability and circularity of buildings and of the impact of possible strategies. They also denote the need for AI as it in the future could accelerate decision making when used.

In this study, potential Digital Twin adopters did not prefer Archetypes 4 (AT 4), 3 (AT 3), or 2 (AT 2). These archetypes may represent configurations or complexity levels that don't meet organisations' strategic or operational needs. Without interest in these archetypes, potential adopters may prefer simpler or more capable Digital Twin solutions that better match their immediate goals and resources in the circular-built environment.

	Intv. 4	Intv. 5	Intv. 7	Intv. 10	Intv. 12	DT wanted	Intv. 1	Intv. 2	Intv. 3	Intv. 6	Intv. 8	Intv. 9	Intv. 11	Intv. 13	DT used
Digital Twin Usage	No						Yes								
Archetype 1	0	1	0	1	0	2	0	0	0	1	1	0	0	1	3
Archetype 2	0	0	0	0	0	0	1	1	0	0	0	0	0	0	2
Archetype 3	0	0	0	0	0	0	0	0	1	0	0	1	1	0	3
Archetype 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Archetype 5	1	0	1	0	1	3	0	0	0	0	0	0	0	0	0
Totals	1	1	1	1	1	5	1	1	1	1	1	1	1	1	8

Table 7: Archetype compared to early and potential adopters

5.4 Barriers and Challenges

In the following chapter we will analyse the Barriers expected by the potential user of Digital Twins and the challenges experienced by the early adopters. For this the expected Barriers and experienced Challenges discussed previously were separated into several sub aspects. This was done by gathering all barrier and challenges named during the interviews, categorizing them according to the generic obstacles named during the previous chapter and then this was comparison was used establish several sub aspects that were more specific to those named by the interviewees. These were used to code the interviews and highlight recurrence. It should be stated that after conducting the interviews the categories for barriers and challenges established in the previous chapter lacked a degree of specificity. For safeguarding & ownership and Financial &Economic categories, sub aspects were established according to which the Barriers and Challenges mentioned by interviewees were indexed. Additionally additional clarification of several of the categories was created as in this chapter we will discuss the sub aspects quickly followed by the results quickly. It should be stated that in this phase the barriers and challenges to the implementation of digital twins was separated from the barriers and challenges to the implementation of circularity strategies, as the focus of this thesis is the use of digital twins.

For **safeguarding of data and the issue of ownership**, a few subcategories were created as this was a broad concept. This category encompassed whom has access to the data, how the data is secured and issues related to unclear ownership of data.

- Data Privacy
- Cyber Security
- Data Ownership

For the **lack of standardised data standards and tools** there was additional clarification needed as it was also similar in description to diversity within source systems. Lack of Data standards refer to the diverse methods that specific types of data (usage, climate, energy usage, etc.), are gathered represented and stored.

For **diversity within source systems (DWSS)** there is a focus on the different types of data contained within digital twins. These different types of data differ on the basis of what they say but can also be due to the type of data differ on basis latency, typology and accuracy. These all need to be integrated coherently into a single digital twin that is a reflection of reality.

The category **Financial and Economic challenges** was also too broad. This category took into account the ability to pay, the perceived lack of available vendors of these technologies and the lack of a clear investment strategy with a clear method or definition on the return on investing in these technologies for circularity.

- Financial capacity
- Lack of capable market partners
- Lack of a clear business model

Cultural challenges as stated was often linked with the unwillingness of the organisations in the built environment to adopt new technologies. This technological hesitancy is the barrier or challenge for the implementation of new technologies.

In regard to **Regulatory Challenges**, the challenges or barriers are meant to reference the lack of a legal framework that encompasses the legal definitions of terms (which affects the other barriers) and standards (making wider adoptions not just easier but also a requirement).

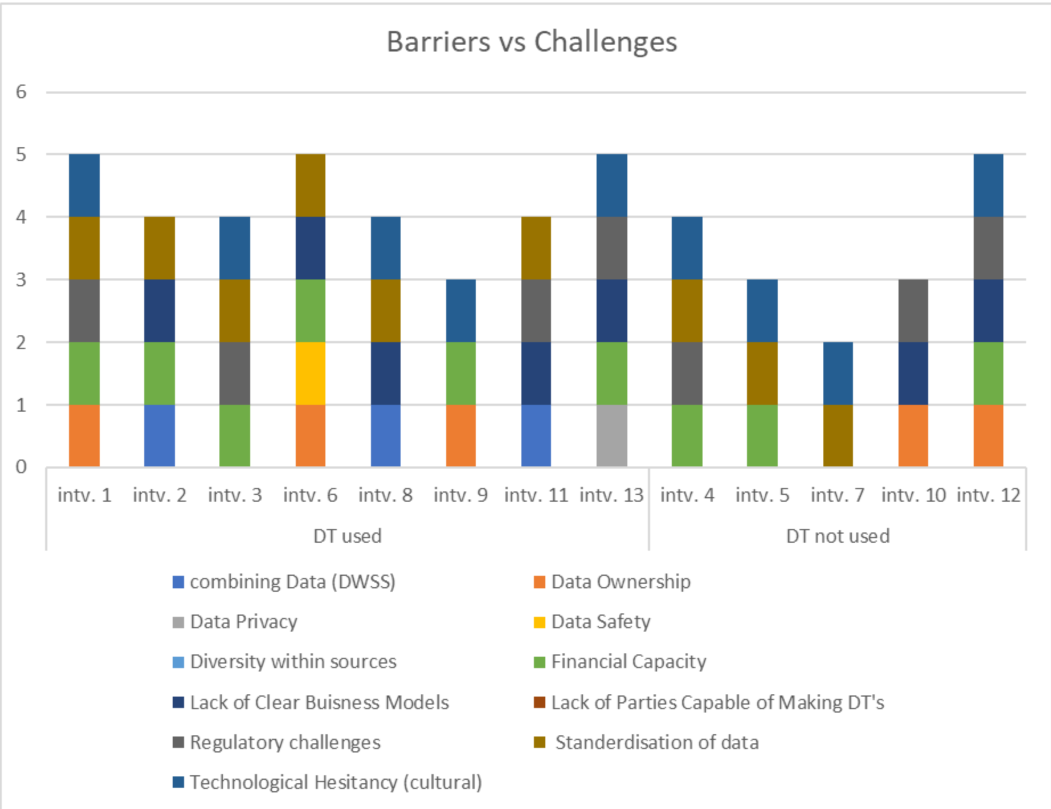

Figure 11: Occurrence barrier and challenges

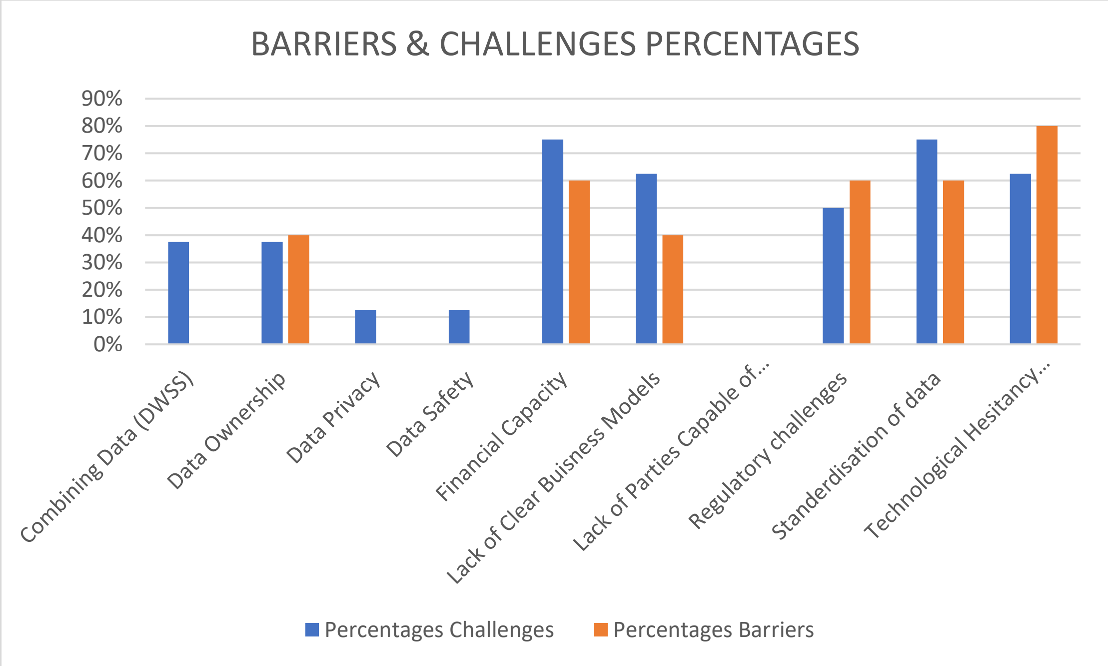

Figure 12: percentage occurrence barrier and challenges

Categories	Total Occ. Challenges		Total Occ. Barriers	
combining Data (DWSS)	3	38%	0	0%
Data Ownership	3	38%	2	40%
Data Privacy	1	13%	0	0%
Data Safety	1	13%	0	0%
Financial Capacity	6	75%	3	60%
Lack of Clear Business Models	5	63%	2	40%
Lack of Parties Capable of Making DT's	0	0%	0	0%
Regulatory challenges	4	50%	3	60%
Standardization of data	6	75%	3	60%
Technological Hesitancy (cultural)	5	63%	4	80%

Table 6: percentage and occurrences barrier and challenges

The challenges encountered by interviewees using Digital Twins (DTs) varied, with some issues being more prevalent than others. Financial capacity and data standardization emerged as the most significant challenges, each affecting six of the eight interviewees (75%). Specifically, **Interviewees 1, 2, 3, 6, 9,** and **13** reported difficulties related to the high costs and complexities associated with these aspects. The lack of clear business models and technological hesitancy, which reflects cultural resistance to adopting new technologies, were also prominent, each impacting five interviewees (63%). These challenges were noted by **Interviewees 2, 6, 8, 11,** and **13** for business models, and by **Interviewees 1, 3, 8, 9,** and **13** for technological hesitancy. Regulatory challenges were identified by four interviewees (50%), including **Interviewees 1, 3, 11,** and **13**, highlighting the difficulties in navigating complex regulations associated with DT implementation. Data ownership and the challenges of combining data (DWSS) were each reported by three interviewees (38%). Data ownership was a concern for **Interviewees 1, 6,** and **9**, while **Interviewees 2, 8,** and **11** struggled with integrating data from diverse sources. In contrast, data privacy and data safety were less commonly reported, each affecting only one interviewee (13%). **Interviewee 13** was concerned with data privacy, while **Interviewee 6** highlighted data safety as a challenge. Notably, none of the interviewees reported issues with finding parties capable of making DTs, suggesting that this was not a significant barrier in their experiences. This distribution of challenges underscores the multifaceted difficulties encountered in the adoption and implementation of Digital Twins, with financial and technological barriers being the most critical across the interviewed participants.

The analysis of interviewee responses reveals several key barriers impacting the adoption and implementation of digital twin technologies. A predominant challenge is **technological hesitancy (cultural)**, experienced by **Interviewees 4, 5, 7, and 12**, with an occurrence rate of 80%. This suggests a significant cultural reluctance to embrace new technological advancements. Financial constraints also present a notable issue, reported by **Interviewees 4, 5, and 12,** affecting 60% of the sample. Regulatory challenges are similarly prevalent, impacting **Interviewees 4, 10**, and 12, and reflecting concerns regarding compliance and legal considerations. Data standardization emerges as another critical barrier, affecting **Interviewees 4, 5, and 7,** with a 60% occurrence rate, indicating that inconsistent data practices hinder effective technological integration. Additionally, challenges related to **data ownership** and the **lack of clear business models** are reported by **Interviewees 10 and 12**, each with a 40% occurrence rate. These issues underscore concerns over data management and the need for well-defined financial and operational strategies. In contrast, issues such as digital twin usage, combining data, data privacy, data safety, and the lack of capable parties to develop digital twins were not reported by any interviewees, suggesting these may not be prominent barriers within this context. This comprehensive overview highlights the multifaceted nature of challenges facing technology adoption and the need for targeted solutions to address these barriers effectively.

5.5 Additional & Missing Barriers and Challenges

In this paragraph the barriers that were mentioned by potential adopters will be presented, specifically barriers mentioned by interviewees that could not be categorized into specific groups.

Interviewee 4 stated " Yes data is a solution, however, it is also a barrier. For example, my colleague is currently dealing with this. For example, you have received a Bim model and 5 Gigabytes of data, you would say this is a large amount of data, however it is still insufficient to create detailed material passports". This references that in order to facilitate the circular services they provide and in order to implement the digital twin subcomponents, in this case MP's, there is a lack of data, this could be due to the client themselves not possessing the necessary data about their own structure.

Furthermore, the interviewee stated " Because the BIM model is made in such a way that it is just sufficient for construction, and I expect it is also very important in the design phase because an architect is going to draw all kinds of windows and frames and the installation specialist says, I have to make radiators for those frames. They really enjoy the accuracy of a BIM model. Soon the men will come with the screwdrivers and pliers, they will ultimately build it, and they have no interest in the BIM model at all. They just say, oh, okay, this is what we have to make. These are the drawings. We're going to solve it practically here. We're just going to talk about it. We are going to arrange for the heating to be turned on here in two weeks, and that it will have double glazing. And how we arrange that is up to them all to decide. And then you can have such a beautiful and good BIM model. Ultimately, that BIM model is worthless from that moment on, because it is no longer up to date.". This was mentioned by the interviewee to illustrate the inefficiency currently in the creation of an accurate digital representation of a building. It from the initial construction is already deviating from preconstruction models and data. This then for them leads to additional cost now, making their current process already more expensive and time consuming. So, the interviewee here states that data that is or can be delivered is incomplete and inaccurate when considering built structures, forming a barrier when trying to create digital representations making it in turn a barrier to the creation of Digital Twins.

Interviewee 10 also mentioned a barrier related to this issue. the interviewee stated " That is the input for those digital twins and for those databases. It is just missing. That material information. And if you want to create a digital twin of an existing building, that technology is there, but the information you have to put into it is often missing. And when, for example, you want to apply such a point cloud technology for this. Or you want to do all kinds of tests. To get the material behind it. Then the question is who will pay for it. And what do we ultimately want to achieve with it?". Here as mentioned there is a lack of information that can be provided for existing buildings which forms a barrier and has knock on effects exacerbating other barriers such as financial capacity and making a business case for it.

Interviewee 12 also mentioned data availability as a barrier by stating the following, "Well, if you look at the acceptance of these types of models. A policy can focus on mandating the availability of information. The food industry, et cetera, et cetera. On the basis of public health, it has been mandatory for a long time to make information available about what is in a product. This is not the case with buildings. When you oblige producers to share information, because then you know whether something is healthy at all, we talk about the construction product, but also how long it lasts and ultimately how it can be reused. Then you have overcome an initial barrier or a threshold to make your model better and also more useful in the future." By this statement the interviewee indicated that the due to lack of legal madidates for producers of building components and buildings to share information there is a lack of available data, which in turn impacts the usability and feasibility of digital twins for their strategies.

Lack of data input could be an additional overarching barrier? – specifically linked to the DT's for existing buildings - Put in discussion – people involved with design and build don't seem to mention lack of

In the following paragraph we will discuss the challenges experienced by early adopters that did not specifically fit into the specific categories identified during the literature review.

Interviewee 2 stated " Because it requires a lot of data, and the data doesn't exist, or it's difficult to collect. So, for them, this is how I most of the time see within different stakeholders, that for them it's not clear, or it's too abstract. So, they cannot really see the real benefits, and that is maybe a limitation still, you know." This references the lack of available data when creating a digital as a challenge that is interconnected with other barriers, such as cultural and business case challenges.

Interviewee 8 stated that " the data already exists". He stated that creating Digital Twins requires detailed information for existing buildings, when trying to apply their circular strategies and create digital twins there is often a lack of data available in a clear and accessible manner. Details such as material age or adjustment made by tenants without the organisation's knowledge adds to this discrepancy. This all adds to the complexity of digital twin implementation especially for existing stock of larger portfolios where possible tenants could have contracts for up to 50 years.

Interviewee 9 stated the following " We really don't have that circular economy yet. What did you say? We really don't have that circular economy yet. I think we have 8% of all activities in the Netherlands that can be labelled as circular. So, the question is if you say you have a euro, should you invest in sustainability developments or should you invest in digitalization developments? But I am very convinced of the development you describe in your model. But little money is still being made with sustainability. So, either there must be a cap on the use of primary raw materials or CO2 must become unaffordable. Then it becomes very interesting to set up all these digital tools." With this quote the interviewee stated that the due to the infancy of the concept of a circular built environment there is a lack of benefit and reason to invest in the development of digital twins for circularity. This is a barrier formed by the slow adoption of circularity in the built environment. These are interlinked with financial challenges.

It should be noted that in regard to the interviews conducted with parties already using Digital Twins there was no lack of capable market parties. In regard to interviewees who do not yet use digital twins there were more unnamed barriers. These were Combining Data, Data Privacy, Data Safety and Lack of capable Market Parties.

In conclusion the unknown barriers and challenges highlighted a lack of data to be provided and the infancy of the circular built environment in the Netherlands as factors impacting the adoption of digital twins. These results will also be further discussed in the next chapter.

5.6 Solutions from Early Adopters

The final segment of the study was conducting interviews to investigate the solutions used by the early adopters of digital twins. Eight interviewees reported utilising digital twins in different configurations. Each subject was questioned about the specific methods they employed to overcome obstacles encountered during the development and implementation of digital twins in their organisation. This chapter aims to analyse the diverse solutions discovered and employed by various interviewees who have already included digital twins into their circular processes. The chapter offers a comprehensive analysis of the specific methods employed to overcome challenges and maximise the benefits of digital twins in promoting sustainability and circularity.

The table provided in this chapter outlines the solutions proposed by different interviewees who have effectively adopted digital twins in their respective businesses. The solutions have been categorized into six primary classifications: Each category, including Data Standards and Integration, Technology and Tools, Financial Incentives and Business Models, Stakeholder Engagement and Change Management, and Regulatory and Legal Aspects, represents a vital factor to consider when establishing digital twins to support circular processes. The importance of Data Standards and Integration is highlighted, emphasising the need to establish common frameworks and ontologies to provide seamless data exchange and interoperability between systems. Several participants emphasised the significance of broadening and standardising Industry Foundation Classes (IFC) to improve decision-making and reduce fragmentation in the administration of digital models. The Technology and Tools category encompasses the practical steps taken to incorporate and enhance digital twin technology within current systems. Potential remedies encompass leveraging advanced IFC models and mobile technology to collect data on-site, alongside with a methodical approach for certain situations. These efforts emphasise the vital importance of technology in enhancing the efficiency and effectiveness of circular processes. The primary focus of Financial Incentives and Business Models is on the economic aspects of utilising digital twin technology. This entails creating systems of rewards, business rationales, and regulatory frameworks that encourage the adoption and advancement of value derived from digital twins. The interviewees stressed the significance of combining financial methods with circular objectives to attain sustainable and profitable outcomes. The significance of Stakeholder Engagement and Change Management resides in the imperative for strategic communication and education to foster the adoption and implementation of digital twins. The solutions in this category emphasise the importance of including both internal and external stakeholders in the process of transitioning to digitisation. They also stress the importance of the sector adopting a new attitude that fully embraces evolving technologies. The Regulatory and Legal Aspects area specifically addresses the external considerations that influence the application of digital twin technology. Government regulations, concerns about data protection, and the implementation of legal contracts are acknowledged as essential elements that can either support or hinder the integration of digital twins in circular practices.

In summary, the table provides a detailed overview of the many and successful approaches used by respondents who have used digital twins to advance circularity. Each solution highlights a unique aspect of the challenges and opportunities encountered in this cutting-edge field, offering valuable insights for businesses seeking to adopt similar techniques.

Numbering	Grouping	Intv.	Solutions
1	Data Standards and Integration	1	Setting and developing communication and data sharing protocols for projects.
2	Data Standards and Integration	1	Steering the integration and development of data standards and sharing protocols.
4	Technology and Tools	1	New technology integration when it is sufficiently developed.
5	Technology and Tools	1	Iterating technologies that are already implemented and improving the way the technology is used.
6	Financial Incentives and Business Models	1	Setting the requirements to form financial incentives to steer the way information and data is provided.
7	Stakeholder Engagement and Change Management	1	Choosing partners that are not innovation averse.
8	Financial Incentives and Business Models	1	Self-financing as a way to circumvent potential constraints that come with external financing.
9	Technology and Tools	2	Working with enriched IFC models as it is an open standard.
10	Technology and Tools	2	Integrating mobile technologies (Tablets) in conjunction with trackers and identifiers such as QR codes for onsite data generation and capture to enrich IFCs.
11	Technology and Tools	2	Using IFCs to enhance interoperability and communication with different platforms and applications.
12	Technology and Tools	2	Using query method to make it easily readable for machines and aid in automating decision-making.
13	Data Standards and Integration	2	Solving data standards and lack of a common taxonomy by creating a common ontology that describes digital twins for circularity purposes and a common computational language.
14	Technology and Tools	2	By analysing how components are represented in IFC files and consulting with stakeholders about necessary data, the team could identify missing parameters in the IFC standard.
15	Data Standards and Integration	2	Creating a standardized approach that prevents fragmentation and inconsistencies when different parties work on digital models for circularity.
16	Data Standards and Integration	2	Expanding the IFC standard itself, helping to standardize how data is handled in digital twins and other digital tools, making it easier for different systems and stakeholders to interact seamlessly and make informed decisions in a circular economy.
17	Data Standards and Integration	2	Mapping the data flow and identifying the key stages and inputs/outputs in the recycling process. They then linked these steps to the Industry Foundation Classes (IFC) standard, which is widely used in building information modeling (BIM).

19	Data Standards and Integration	2	Solving disagreements on terminology around the implementation of circular activities by creating a structured framework based on ontology, logic, and computation.
20	Data Standards and Integration	2	Instead of creating a new ontology from scratch, they decided to integrate these concepts within the existing IFC framework.
21	Technology and Tools	2	Data acquisition through the creation inspector capabilities, based on creating workflows based on the ontology and available technology that allows for the IFCs to be enriched with the necessary and required data creating a true twin by data flowing into the model.
22	Technology and Tools	2	A step-by-step approach, based on the specific use case of the Digital Twin for a circular purpose is mapped onto the taxonomy applying IFC definitions accordingly, and then using IFC to automate decision-making based on established standards.
23	Data Standards and Integration	2	Using open data standards and technologies to avoid conflicts with proprietary intellectual property
24	Data Standards and Integration	2	Identifying the specific circularity goal, the configuration needed and mapping it onto the ontology. Developing a generic, step-by-step methodology that uses open formats like IFC to integrate and address various barriers to implementing digital twins for circular purposes.
25	Stakeholder Engagement and Change Management	3	A change in strategy by focusing mainly on managers of larger portfolios.
26	Data Standards and Integration	3	Based on the project, many partners may be needed, to facilitate cohesive cooperation and usability of data exchanged. Internal data standards are set based on set Object Type Libraries allowing for efficient data management and integration into partner work processes.
27	Technology and Tools	3	Using technology-focused change management to address internal and external (customers) stakeholders.
28	Stakeholder Engagement and Change Management	3	Creating awareness with internal and external stakeholders that the current methods of implementation are not sufficiently efficient.
29	Stakeholder Engagement and Change Management	3	You need to seduce clients and your own internal stakeholders with the vision of digital twins.
30	Stakeholder Engagement and Change Management	3	Change management on a customer level. Educate them on the benefits of technology.
31	Financial Incentives and Business Models	3	There are clients that are currently making the implementation of innovative solutions part of their contracts.

32	Financial Incentives and Business Models	3	Consider the interplay between customer demands and financial incentives.
33	Data Standards and Integration	3	Robust internal data strategy, including the development of a unified data structure to connect various data silos within the company, which is essential for managing and reporting on sustainability efforts.
34	Technology and Tools	3	Leveraging the company's network and interest organizations to promote the development of a data standard across the sector.
35	Regulatory and Legal Aspects	6	The creation of regulations requiring adherence to certain standards drives the adoption of Digital Twins for circular standards.
36	Technology and Tools	6	Expanding government financial incentives and subsidies for implementing technologies.
37	Regulatory and Legal Aspects	6	Allowing certain data to be excluded to provide a measure of data security.
38	Technology and Tools	6	Integrating features that make it attractive for not only the client but also material and component producers, allowing them insight into material usage, thus incentivizing them to allow data about their components to be shared.
39	Regulatory and Legal Aspects	6	Providing data safety and considering the impact on competition if data is shared.
40	Data Standards and Integration	8	When integrating different types of data, programs, and partners, the use of IFC is necessary.
41	Data Standards and Integration	8	Working with a common and generic ontology and data language even if partners are still working with their own versions.
42	Stakeholder Engagement and Change Management	8	Education of partners is necessary.
43	Financial Incentives and Business Models	8	Business theory-oriented approach, meaning that there are financial incentives to be found in reducing transaction costs.
44	Technology and Tools	8	Using the tools currently available and being prepared to adopt standards when the market creates these.
45	Technology and Tools	8	Using technologies that you can, through an iterative process, attune to the specificity and efficiency requirement you specifically need.
46	Regulatory and Legal Aspects	9	There must be commitment to use circular practices, perhaps generated through the creation of circular requirements, as this then drives the need for the technologies.
46	Stakeholder Engagement and Change Management	9	There must be commitment to use circular practices, perhaps generated through the creation of circular requirements, as this then drives the need for the technologies.

47	Stakeholder Engagement and Change Management	9	A shift in thinking necessary to drive the need for the technologies.
48	Data Standards and Integration	11	Focus on scale and information provision rather than strict adherence to a set process.
49	Stakeholder Engagement and Change Management	11	Working with client willingness to pay for the implementation of the technologies.
50	Technology and Tools	11	Working with integrated solutions when the time and money allows for this.
51	Technology and Tools	11	Front and back-end services beginning, and end of life phase need to be linked on a service level.
52	Regulatory and Legal Aspects	13	Government must create a drive for the adoption of these technologies by creating requirements for circular practices.
53	Financial Incentives and Business Models	13	Incentive structures need to be created for passing the added value of digital twins to customers more directly, creating a better business case for them.
54	Data Standards and Integration	13	Data requirements by government can also drive digital twin adoption.
55	Technology and Tools	13	Low latency data inputs for digital twins can avoid the privacy issues that come with continuous monitoring.
56	Regulatory and Legal Aspects	13	For startup-scale companies with tighter financial constraints, prioritizing which capabilities are necessary.
57	Financial Incentives and Business Models	13	Creating a business case that adds value to the customer and the organization is necessary.
58	Financial Incentives and Business Models	13	Creating legal frameworks and agreements is necessary to ensure the client's permission and privacy regarding their data.
58	Regulatory and Legal Aspects	13	Creating legal frameworks and agreements is necessary to ensure the client's permission and privacy regarding their data.
59	Stakeholder Engagement and Change Management	13	Client-oriented approaches to data privacy.

Table 7: Solutions sourced from interviewees

6.0 Discussion & Conclusion

6.1 Discussion

The first point of discussion will be the discrepancies between practice and the theoretical research and frameworks setup in the first part of this thesis. The most immediate realization during the conducting of the interviews was that the frameworks constructed, namely the circularity matrix and the archetypes, did not fully reflect reality. As stated by interviewee 11 when discussing the circularity matrix, reality is not as neat as the boxes of a matrix make it out to be. By this statement they meant that companies or organizations never neatly fit into any of the boxes, that they likely would often fit into multiple boxes and that companies or organizations are to a certain degree flexible as to where they would be active in the matrix, possibly due to the needs of a certain client or project. The same goes for the archetypes, several of the interviewees referenced specific modifications to the archetypes that were their preference. However as will be shown through the discussion below the circularity tool still offers a degree of functionality, specifically as a tool to create a common taxonomy and therefore it facilitates comparisons between interviewees. Additionally, the circularity matrix as a tool could still be beneficial as a tool when using it on a much larger data set or alternatively as a tool for a statistical study on a much larger scale. The archetypes despite the archetype modifications still function as clear indications of the maturity of the digital twins adopted, their use case as perceived or employed and as a way to compare the whom uses or wants similar digital twin. So, keeping these factors in mind the discussion will still reference the circularity matrix supplemented with the general description of the interviewees and the archetypes will also be used with the relevant modifications referenced where relevant.

6.2 Solutions compared to Challenges

The adoption and integration of Digital Twin technologies in the built environment present a complex array of challenges. These challenges span from data standardization to financial constraints, cultural hesitancy, and regulatory hurdles. This chapter explores various solutions proposed to address these challenges and assesses their effectiveness in overcoming the identified barriers. Additionally, it highlights the gaps where challenges remain unresolved, providing insights into areas that require further attention. The numbers in the following paragraph refer to the solution table.

Data Standards and Integration

Data standards and integration are critical for ensuring that diverse data sources within Digital Twin ecosystems are harmonized and effectively utilized. The following solutions have been proposed:

- Setting and developing communication and data-sharing protocols (1).
- Steering the integration and development of data standards and sharing protocols (2).
- Creating a common ontology and computational language for circularity purposes (13, 19, 20).
- Expanding the Industry Foundation Classes (IFC) standard to prevent fragmentation and inconsistencies (15, 16).
- Mapping data flows and linking them to IFC standards in the recycling process (17).
- Creating a unified data structure to manage and report sustainability efforts (33).

These solutions directly address the challenges related to the lack of standardized data standards and tools, as well as the diversity within source systems (DWSS). By setting common protocols and expanding the IFC standard, these solutions aim to reduce fragmentation and improve the integration of various data types into a coherent Digital Twin model.

Unresolved Challenges:

- **Data Ownership:** While these solutions improve data standardization, they do not fully resolve issues related to data ownership. The question of who owns the data within shared systems remains a significant challenge.
- **Data Privacy and Security:** The focus on data standards and integration does not sufficiently address concerns about data privacy and security, particularly regarding unauthorized access and cyber threats.

Technology and Tools

The integration and continuous improvement of technology are crucial for the successful implementation of Digital Twins. The proposed solutions include:

- New technology integration when sufficiently developed (4).
- Iterating and improving existing technologies (5).
- Working with enriched IFC models and mobile technologies for onsite data generation (9, 10, 11).
- Using query methods for machine readability and automation of decision-making (12).
- Adopting a step-by-step approach for specific use cases (22).
- Integrating front and back-end services to connect the lifecycle of a Digital Twin (51).

These solutions are effective in addressing the challenge of **technological hesitancy** by promoting the adoption and iterative improvement of technologies. They also help in integrating new tools and standards, thus enhancing the overall efficiency and functionality of Digital Twins.

Unresolved Challenges:

- **Financial Capacity:** While the iterative improvement of technology may reduce costs over time, these solutions do not directly tackle the challenge of financial constraints, which remain a significant barrier to adoption.
- **Lack of Capable Market Partners:** The availability of market partners who can implement and support Digital Twin technologies is not directly addressed by these solutions. The challenge of finding capable partners remains a critical issue.

Financial Incentives and Business Models

Financial incentives and clear business models are essential for driving the adoption of Digital Twins. The following solutions have been proposed:

- Setting requirements for financial incentives to steer data provision (6).
- Self-financing to avoid constraints from external financing (8).
- Incorporating customer demands into financial incentives (32, 43).
- Creating a business case for Digital Twins that adds value to customers (53, 57).

These solutions address the challenges related to **financial capacity** and the **lack of clear business models** by creating incentives and business cases that encourage investment in Digital Twin technologies. By aligning financial incentives with customer demands and business needs, these solutions aim to make Digital Twins more economically viable.

Unresolved Challenges:

- **Lack of Capable Market Partners:** Although improving business models may attract more partners, these solutions do not directly resolve the issue of a limited pool of vendors capable of delivering Digital Twin solutions.
- **Cultural Hesitancy:** While financial incentives can help overcome some resistance, the deep-seated cultural reluctance to adopt new technologies is not fully addressed by financial strategies alone.

Stakeholder Engagement and Change Management

Effective stakeholder engagement and change management are crucial for overcoming resistance to new technologies. The proposed solutions include:

- Selecting innovation-friendly partners (7).
- Educating stakeholders about the benefits of Digital Twins (30, 42, 46, 47, 49).
- Focusing on technology-oriented change management (27).

These solutions are designed to address the challenge of **cultural hesitancy** by fostering a positive attitude towards innovation among stakeholders. By selecting partners who are open to new technologies and educating others on their benefits, these solutions help mitigate resistance to change.

Unresolved Challenges:

- **Data Ownership:** While stakeholder engagement is important, it does not resolve disputes over data ownership, which requires more formalized agreements and legal frameworks.
- **Regulatory Challenges:** Stakeholder engagement and change management are necessary, but they do not address the absence of a comprehensive regulatory framework that governs the use of Digital Twins.

Regulatory and Legal Aspects

A robust regulatory and legal framework is essential for ensuring the secure and standardized use of Digital Twins. The following solutions have been proposed:

- Creating regulations requiring adherence to standards (35).
- Providing data safety while considering the competitive impact of data sharing (37, 39).
- Establishing legal frameworks and agreements to ensure data privacy (58).

These solutions directly tackle the challenge of **regulatory and legal aspects** by proposing the creation of standards and legal agreements that govern the use of Digital Twins. By addressing data safety and privacy concerns, these solutions aim to create a more secure and standardized environment for Digital Twin implementation.

Unresolved Challenges:

- **Data Ownership:** Although regulatory frameworks are proposed, they do not fully resolve issues of data ownership, particularly in collaborative environments where multiple parties contribute to and access data.
- **Financial Capacity:** Regulatory frameworks, while necessary, do not directly address financial constraints, which remain a significant barrier to wider adoption.

Gaps and Unresolved Challenges

While the proposed solutions cover a broad range of challenges, several key areas remain unresolved:

Data Ownership: Despite efforts to standardize data and create legal frameworks, the issue of data ownership remains unresolved. Clear guidelines and agreements are needed to define who owns and controls data within shared Digital Twin systems.

Data Privacy and Security: The solutions largely focus on data standardization and technological integration but do not adequately address concerns around data privacy and security, particularly in protecting against unauthorized access and cyber threats.

Financial Capacity: While financial incentives and business models are discussed, there is no direct solution that addresses the fundamental issue of financial capacity, particularly for smaller organizations with limited budgets.

The solutions proposed in this chapter represent significant steps towards overcoming the challenges associated with Digital Twin implementation in the built environment. However, several critical gaps remain, particularly concerning **data ownership, privacy and security, the availability of capable market partners, and financial capacity.** Addressing these unresolved challenges will be crucial for the successful and widespread adoption of Digital Twin technologies. Further research and strategic initiatives are needed to fill these gaps and ensure that the full potential of Digital Twins can be realized in creating sustainable, efficient, and circular built environments.

Comparison between experienced solutions and barriers

The solutions provided make significant strides in addressing several key challenges and barriers associated with the implementation of Digital Twins, particularly in areas like data standardization, technological integration, and financial incentives. **For instance, the creation of common ontologies, the expansion of IFC standards, and the development of data-sharing protocols directly tackle the challenges of lacking standardized data tools and the diversity within source systems.** Additionally, **technological improvements and change management strategies** help mitigate **cultural resistance to adopting new technologies.** However, despite these advances, several critical barriers remain unresolved. Notably, **issues of data ownership, particularly in collaborative environments,** are **not** fully addressed. Concerns around **data privacy and cybersecurity are also insufficiently covered**, as the focus remains on integration rather than securing and protecting data. Financial capacity, especially for smaller organizations, continues to be a barrier, with current solutions offering limited relief for budgetary constraints. Moreover, the lack of capable market partners is not directly tackled, posing a challenge to the widespread adoption of Digital Twins. While the proposed solutions make substantial progress, these gaps highlight the need for further development and strategic efforts to fully overcome the remaining barriers

6.3 Comparison between Early Adopters and Potential Adopters

Early adopters Archetype choice comparison

In this Section we will discuss the relevant choices made by early adopters of digital twin archetypes. This will be done by comparing them to the descriptions of each of the interviewees.

Comparison point : Choice for archetype 2

Interview 2: Head of Research Unit - Used AT 2 Interviewee 2 was as mentioned the head of research in technology development and consultancy firm for companies active in the circular built environment. The interviewee stated that they were currently using a basic analysis twin and had developed automation of decision making processes. However, this method was based system that did not intergrate AI, but rather the setting of standards to test components against. A modification to the archetypes developed was that DMP, s are also looped into their material system. They did state that were actively working on maturing their model into a Predictive analysis twin and that they were interested in implementing AI and were also working on integrating MP's into DMP's. IT could be stated based on the interview that this organization has developed a solid foundation first and building on top of that to develop more advanced and integrated version s of digital twins.
Interview 1: Project Developer & Director - Used AT 2 Interviewee 1 was as mentioned a real estate branch of a large architectural firm with a specialization in (re)development of residential, commercial, office, and leisure projects, operating as both risk-bearing and delegated developers, with a focus on quality, circularity, and commercially viable sustainability concepts. Provides comprehensive management and advisory services in building and area development. The interviewee stated that they used AT 2 "Basic Analysis Twin" with a modification, namely the use of material platforms. This is currently done manually but being developed to be integrated. Furthermore, there was stated that they wanted to further develop it into a high-fidelity twin.

By comparing interviewee 1 and interviewee 2 who are early adopters of digital twins is possible to identify points of comparison between the two organizations the interviewees are associated with. AT 2 was the "Basic Analysis Twin". Interviewee 1 was active in a larger firm which had the capacity to employ these technologies and interviewee 2 was active in an organization focused on developing these technologies. This could be possible explanations for the choice for this specific archetype.

Comparison point: Choice for AT 3

AT 3'the predictive analysis twin, is as stated in the quotes used by two very large organizations and one that is compared to the others small but focused on innovating within the circular built environment. Interviews 3 and 9 were conducted with large firms that have the capacity to develop it and employ this more advanced twin, interview 11 was conducted with a smaller firm but the AI predive components were provided during the exploitation of the real estate. The 2 larger firms both were involved with the large scale development of real estate and infrastructure and this scale could allow for the benefits to be more apparent and the financial impact of developing these technologies to be relatively small.

Interview 11: Owner and Director & Used AT 3

Interviewee 11 was the Owner of two companies in the Dutch Circular Built Environment. One company is an architectural firm focused on a sustainable future, and the other is a hybrid living concept for the modern sustainable city. The interviewee stated as mentioned above that they use AT3, predictive analysis twin, all relevant technologies were present, including AI which was used in support of activities during the use phase. The interviewee also stated that the twins were digitally linked to a material platform, namely the Dutch National Database for materials. They models consist of sub models which are the components that communicate bilaterally to ensure that the data is up to date.

Interview 9: Program Manager, Sustainability Program Manager & used AT 3

This interviewee was also employed at a major construction firm in the Netherlands as a Sustainability Program Manager. This firm was also stated to have a focus on sustainability and innovation. The use AT 3 in support of their infrastructure projects and want to intergrate it also into realestate as well. Additionally, internally thei already possess and intergrate a Material Platform to facilitate material flow between the many sites where this organization is active.

Interview 3: Program Manager of Digital Construction & Used AT 3

As stated above the organization this interviewee was linked to, the was a very large construction firm with a focus on sustainability and innovation. The interviewee was a manager involved with implementing digital twin technologies. This interviewee stated that the used AT 3, the predictive analysis twin. They currently employ this type of twin in support of infrastructure projects and their real estate. Additionally, they want to integrate their twins into a DMP to be part of a material ecosystem.

Comparison point: Choice for AT 1

The users of this archetype that are actively developing real estate are both relatively young companies. Both are focused on sustainable and circular practices through the lens of innovation. Their stated focus on innovation paired with their relative youngness of these organizations might explain their use of AT 1 as the capacity to develop a more advanced twins is still being developed, but their focus on innovations requires them to use it. Tracking of materials is key for all three of the interviewees, this offers some overlap.

Interview 6: Product Manager & used AT 1 This interviewee was employed at a company offering a digital platform for managing material passports to companies active in the circular built economy. They promote sustainability in construction through consulting and advisory practices, facilitating material tracking throughout building lifecycles, and advocating for circular business models. However, their platform focused orientation necessitates modifications such as cloud computing and their functionality also means that their model includes a Digital Material Platform.

Interview 8: Operations Director & used AT 1 Interviewee 8 worked for a company focused on modular wood construction. It facilitates the transition to circular building through the development and provision of modular construction services. The interviewee stated that they are not a very large organization and are currently endeavouring to scale up. The interviewee stated clearly that they used the first on and stated that they others are logical, but the financial aspect or business case is not yet fully clear to them.

Interview 13: Sustainable Business Developer and Member of Commercial and R&D Team & used AT 1 The company which the 13th interview was conducted with was a relatively young start up specializing in the production of three-story houses within their factory. Their focus was Utilizing cross-laminated timber (CLT) as the primary building material, manufacturing fully equipped homes within the factory, streamlining the building process. The interviewee who was active in both the research and development side and the commercial side stated that the company currently employs the design and repository twin. And are currently working with a partner to base the Material Passports and models of their houses on a shared platform. They explicitly stated that Translation applications are part of this process.

Overall comparison early adopters

Archetypes 2 and 3 appear to be used by parties that either have the benefit of size or organizational specialization, meaning that due to there more complex nature compared to the first archetype there is a greater need for financial or technical capacity. When considering the early adopters Archetype 1 which could be considered a less mature model was being used by relatively young but innovation oriented companies and by a company that specifically focused on delivering a type of technological service. The younger organizations all stated that they wish to adopt more mature and capable archetypes. It could be considered that for the adoption of digital twins there is a need to start with less mature models and from there develop more advanced archetypes by modifying it and gradually adding new capabilities. If organizations are smaller might be necessary to adopt the less mature archetypes, with the modifications necessary to fit your needs, and then building on top of it.

Potential adopters archetype choice comparison

Below we discuss the digital twin archetypes preferred by potential adopters, and we will also discuss the relevant description of each of the interviewees.

Comparison point: preference for AT 1

The two organizations that stated that they preferred AT1 are very different organizations, they have first is a part of a larger organization that focuses on the interior of buildings and the second was a research organization. The first was perhaps focusses on interiors who have shorter life cycles and the second stated that they wished to use a second wished to develop a specific basis for an integrated platform which could be further developed. This could indicate that they perceive AT 1 as model either suited as a starting point or as a model that could be adopted for shorter life cycles. It could be stated that this choice is based on ease of adoption and adaptability. One for further development and one for changes in the relevant structure's composition.

Interview 5: Lead Interior Design Team Associate Director & AT1 Interview 5 was conducted with a representative of a Dutch branch of a large international firm. The interviewee who was the lead of the interior design team stated that sustainability and circularity were key facets of their practices. They Specialized in creating interior spaces, calculating costs, and considering sustainability factors such as Life Cycle Analysis (LCA) to support circularity strategies. As they life cycle of interiors is a lot shorter, and its proper redevelopment could extend the lifespan of the exterior, material flows are more frequent compared to exteriors. For this the interviewee stated that they would like to employ AT 1 to support their circular activities, with additional material platform integration.

Interview 10: Researcher in Reliable Structures Department & AT1

Interviewee 10 represented a research institution focused on applied scientific research. It conducts studies on circularity and construction, particularly in infrastructure and buildings, and is involved in projects promoting sustainable steel production and sustainable transportation methods. They do already have digital twins in house however they stated not to use it is support of their circularity-oriented activities. When asked what digital twin archetype best to fit their activities the interviewee stated that AT 1 was, they type they wanted. They stated that they wanted this as their priority when developing a digital twin for circularity would be the gathering and storing comprehensive amounts of data and making it accessible. This indicates that they consider it necessary to develop a specific circularity oriented digital twin from the ground up instead of using the technology they already have in house. They would however likely benefit from having the expertise and capacity to develop this specific twin.

Comparison point: preference for AT 5

The three organisations exhibit a notable convergence in their utilisation of the fifth archetype of digital twin (AT 5). Their shared emphasis on sustainability, circular economy principles, and advanced material management requires the utilisation of an exceptionally powerful digital twin capable of effectively managing and optimising the lifespan of materials in real-time. The task of Interviewee 4 involves promoting the reuse of materials and optimising the flow of materials. This requires a digital twin that offers detailed data throughout the whole lifecycle of materials. This ensures that materials may be recycled effectively within a constantly changing material ecosystem. Interviewee 7, who specialises in enhancing environmental performance in buildings, considers the AT 5 crucial for integrating data from different sub-technologies to effectively manage material lifecycles. This integration is critical for achieving their circular economy objectives. Interviewee 12, who works in the field of sustainability consultancy, believes that the AT 5 is essential for producing AI-driven insights and integrating data within a connected ecosystem. This, in turn, improves their capacity to provide clients with advice on sustainable practices. The shared characteristic among these interviewees is their requirement for a digital replica that not only monitors and forecasts the condition of materials throughout their entire lifespan but also seamlessly connects with wider material platforms and ecosystems and can provide complex solutions to help them facilitate their clients. This common necessity arises from their responsibilities in promoting sustainability, maximising material utilisation, and progressing circular economy strategies in the construction and built environment industries.

The choice for digital twins seems for Archetype 5 be predicated on the need for complex outputs while the choice for the first archetype seems to be predicated on the ease of implementation of digital twins and the need for adaptability.

Interview 4: Team Leader of Circular Team & AT 5

Interviewee 4 worked at an engineering firm specializing in circularity. Specializes in the reuse and repurposing of materials, facilitating material reuse for clients, and optimizing material flows to promote sustainability in construction projects. The interviewee indicated that for these purposes they needed a very advanced high fidelity digital twin, the AT5. This is because they suspect that they would need a digital twin that does not only contain information at the end of life of a structure but would need a twin that would be integrated and that would contain information across its life span. Furthermore, they would need it to be integrated real time into material ecosystem.

Interview 7: Building Physics and Sustainability Consultant, Unit Manager & AT5

Interviewee 7 represented a leading advisory firm focusing on building physics, acoustics, and sustainability. Their focus was optimizing the environmental performance of buildings through advanced material selection and design strategies, working on both new construction and renovations, committed to circular economy principles. The interviewee stated that they did know about the technology and had been following it for 20 years and considered its implementation the holy grail for supporting their circular activities. They use some of the sub technologies, but they are not integrated. They stated that the high-fidelity twin would best fit with their activities. Specifically, it allows for the exchange of data with digital material platforms, which is crucial for managing and predicting the state of materials before they reach the end of their lifecycle. This capability aligns with their focus on sustainability, material management, and the circular economy, as it enables more efficient use of resources and better planning for the future.

Interview 12: Senior Sustainability Advisor

Interview 12 was conducted with a consultancy and advisory firm specializing in sustainability and environmental aspects in buildings and construction. They provide services such as advising clients on policy and implementation, developing methodologies for environmental performance assessment, and offering software applications. They worked with different parties in the construction chain, ranging from municipalities and corporations to architects, developers and investors. They are currently exploring how to properly implement digital twins but their wish to gain the capacity to generate AI driven advice based on integrated AI and Data available in an interconnected ecosystem made the AT 5 the most fitting archetype.

Overall comparison Potential Adopters

When comparing the potential adopters three points of notice become clear when considering their choice for a certain archetype.

The first point of notice is the degree of complexity of the archetype as a feature. AT1 appears to be chosen for its relative simplicity and ease of adaptability and implementation. In contrast AT 5 seems to be specifically preferred for its complexity as it offers the ability to handle and process intricate and real time data requirements.

The second point was the organizational perspective of the interviewees. The preference for AT1 seemed to correlate with a more specific and narrow focus (for example interiors or research), while the preference for AT seemed to correlate with a broad operational profile covering systemic issues like sustainability and life cycle management.

The last point of notice became evident when considering a more technology-oriented perspective. AT 1 was apparently seen as a starting point for further development or as a solution for shorter life cycles. In contrast AT 5 was preferred for its advanced integration capabilities and to connect with broader ecosystems to provide detailed and complex outputs. Additionally, none of the interviewees stated specifically that they themselves wanted to develop it. This could be due to them themselves wanting to adopt these technologies as ready to use packages.

Overall comparison Potential and Early Adopters

The selection of particular archetypes of digital twins by early adopters and potential users seems to be impacted by various aspects, such as the size and specialization of the organization, its financial and technological capabilities, and the intended purpose of the technology. Typically, larger organizations or those with a high degree of specialization are the ones who are the first to use Archetypes 2 and 3. These organizations have the requisite financial and technical resources to effectively handle the intricacies connected with these more sophisticated archetypes. The use of these models indicates a willingness to invest in advanced systems that provide intricate, predictive, or integrated functionalities, which are crucial for extensive operations or specialized jobs that require exceptional accuracy and thorough data handling.

On the other hand, individuals or organizations that are younger and driven by innovation, or those who offer specific technical services, are more likely to be early adopters of Archetype 1. These organizations frequently start with less developed models such as Archetype 1 because it is relatively easier to deploy and has fewer starting costs. Archetype 1 provides a foundational framework that may be adjusted and progressively improved as the organisation expands or as the requirements of its digital counterpart become more intricate. This method enables smaller organisations to participate in the digital twin landscape without the immediate requirement for significant financial or technological commitment, offering a flexible solution that may adapt and grow over time.

When potential adopters are evaluating digital twins, the selection of archetype also depends on their particular requirements and the setting of their organization. Organizations that have shown interest in Archetype 1 include a subsidiary of a larger organization specializing in interior design and a research institution. Archetype 1 is considered appropriate for situations where quick adaption and shorter time frames are crucial, as it emphasizes interiors that have shorter life spans. Similarly, the research organization considers Archetype 1 as a fundamental model that can be further developed into a more comprehensive platform. This suggests that the organization prioritizes ease of adoption and the potential for future development when making decisions.

The adoption of Archetype 5, however, is motivated by the necessity for exceptionally sophisticated capabilities. Organizations that embrace this paradigm, such as those that prioritize sustainability, circular economy principles, and complicated material management, need digital twins capable of efficiently managing and optimising material lifecycles in real-time. These digital twins should be able to combine data from many sources and provide insights using artificial intelligence. However, for prospective adopters, particularly advising companies that do not have specialised development resources, Archetype 5 may be seen more speculative. These companies might see the technology as an ambitious goal because of its sophisticated features, but they may not fully take into account the actual difficulties of putting it into practice, such as the requirement for significant technical infrastructure and development resources. This indicates that these companies acknowledge the worth and promise of Archetype 5, but their current abilities may not yet be in line with the requirements of such an advanced system.

Ultimately, the selection of a digital twin archetype is determined by factors such as the organization's scale, expertise, financial and technological capabilities, as well as the particular use case or lifecycle requirements. Early adopters that possess ample resources and have more intricate requirements are inclined to go for advanced archetypes such as AT 2, 3, or 5. Conversely, smaller or less specialised organisations may begin with simpler models like AT 1, which provide superior flexibility and require less initial investment. Prospective adopters, particularly those in advisory positions, may find Archetype 5 appealing due to its potential for expanded capabilities, rather than its immediate feasibility. The phased method facilitates the gradual implementation and customisation of digital twins, allowing organisations to expand their capabilities as they grow or as their requirements change.

6.4 Comparing Matrix Positions & Archetype Barriers and Challenges

6.4.1 Matrix position and Archetype

Potential adopters vs Archetype

	Pre-Build	Construction	USE	End of Life
Slow	AT 1 Int.13; AT 1 Int.8	AT 1 Int.13; AT 1 Int.8	AT 1 Int.13; AT 1 Int.8	AT 1 Int.13
Narrow	AT 1 Int.13	AT 1 Int.13	AT 1 Int.13	AT 1 Int.13
Close	AT 1 Int.13; AT 1 Int.8; AT 1 Int.6	AT 1 Int.13; AT 1 Int.8	AT 1 Int.13; AT 1 Int.8	AT 1 Int.13
Regenerate	AT 1 Int.13; AT 1 Int.8; AT 1 Int.6	AT 1 Int.13; AT 1 Int.8	AT 1 Int.13; AT 1 Int.8	AT 1 Int.13

Figure 13: Archetype 1 choice early adopters compared to matrix positions

Early adopters of Digital Twins (DTs) across the three archetypes exhibit diverse approaches and face a range of challenges as they navigate the complexities of implementing these technologies. In Archetype 1, the companies predominantly operate in the early phases of the building lifecycle, focusing on sustainability and circularity. For instance, Interviewee 6's firm is centred on creating material passports through digital twins to assess the sustainability of building materials, while Interviewee 8's company extends this focus to modular residential real estate, emphasizing biobased materials and longevity. Interviewee 13's approach is even more comprehensive, integrating Close, Narrow, Slow, and Regenerate strategies across all construction phases. However, despite these innovative applications, the challenges experienced by these firms are pronounced. The lack of clear business models is a pervasive issue across all three interviewees, underlining the uncertainty in translating the potential of DTs into viable economic frameworks. Additionally, financial constraints, data ownership and safety, and technological hesitancy, particularly of a cultural nature, further complicate their efforts. These barriers highlight the difficulties in aligning cutting-edge technology with existing organizational and industry structures.

	Pre-Build	Construction	USE	End of Life
Slow	AT 2 Int.2; AT 2 Int.1	AT 2 Int.2; AT 2 Int.1	AT 2 Int.2; AT 2 Int.1	AT 2 Int.2; AT 2 Int.1
Narrow	AT 2 Int.2; AT 2 Int.1	AT 2 Int.2; AT 2 Int.1	AT 2 Int.2; AT 2 Int.1	AT 2 Int.2; AT 2 Int.1
Close	AT 2 Int.2	AT 2 Int.2	AT 2 Int.2	AT 2 Int.2
Regenerate	AT 2 Int.2; AT 2 Int.1	AT 2 Int.2; AT 2 Int.1	AT 2 Int.2; AT 2 Int.1	AT 2 Int.2; AT 2 Int.1

Figure 14: Archetype2 choice early adopters compared to matrix positions

Archetype 2 companies are characterized by their holistic and integrated approach to the building lifecycle, with a strong emphasis on sustainable construction and the extension of product lifecycles. Interviewee 1's architectural office utilizes digital twins to maintain dynamic, up-to-date models throughout the building's lifecycle, focusing on slow loop, narrow loop, and regenerative strategies. Interviewee 2's technology-oriented company similarly employs digital twins to enhance decision-making and facilitate the integration of various technologies. However, the challenges these early adopters face are distinct yet overlapping. Both interviewees identify financial capacity as a significant challenge, mirroring concerns seen in Archetype 1. Additionally, while Interviewee 1 raises issues related to data ownership, regulatory compliance, and technological hesitancy, Interviewee 2 focuses on the difficulties of combining diverse data sources and the lack of clear business models. The emphasis on standardization of data by both interviewees reflects a broader industry-wide challenge in ensuring consistent and interoperable data formats, crucial for the effective deployment of digital twins across diverse applications.

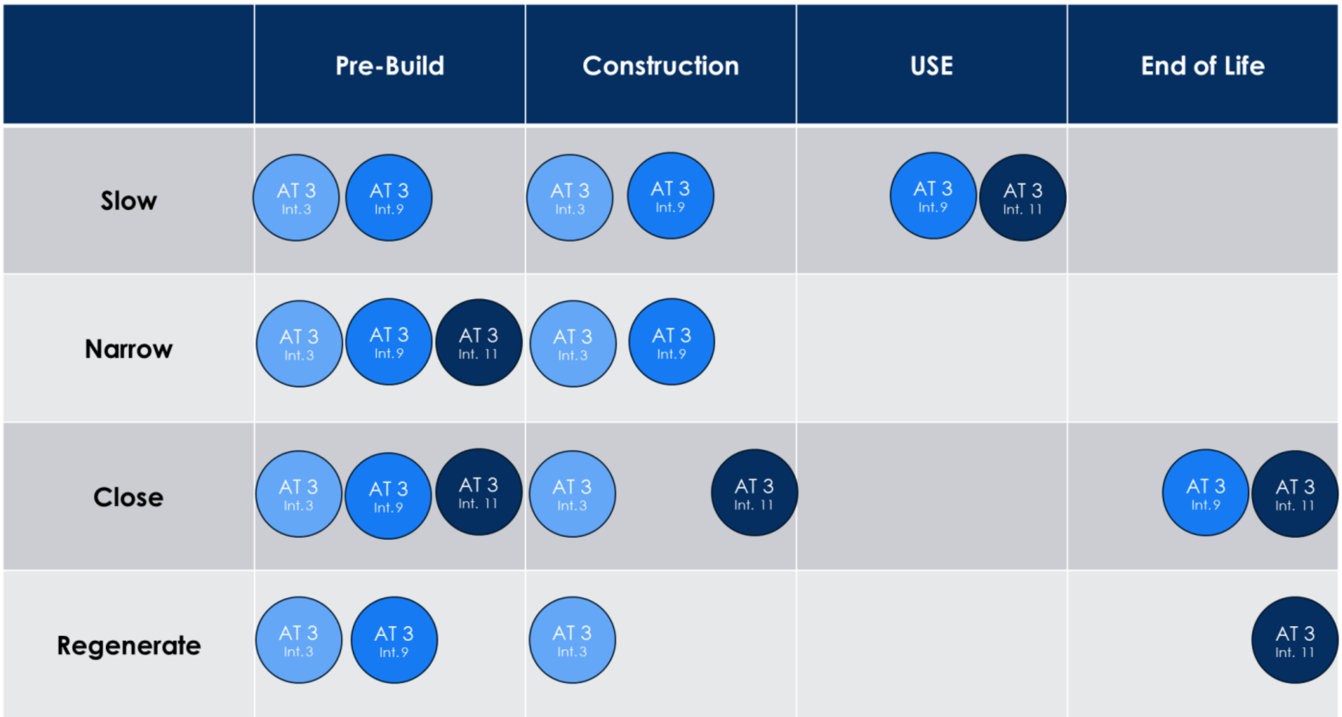

Figure 15: Archetype 3 choice early adopters compared to matrix positions

In Archetype 3, the focus shifts toward large organizations that integrate DTs across various phases of the building lifecycle, often with an emphasis on predictive analytics and the use of AI and IoT technologies. Interviewee 3's organization employs predictive analysis twins, primarily in infrastructure projects, with plans to extend to real estate, while Interviewee 9's firm is in the experimental phase of using AI and IoT technologies in digital twins. Interviewee 11's company, on the other hand, is more advanced in their use of digital twins for lifecycle management in circular real estate. The challenges faced by these companies are multifaceted. Financial capacity, once again, emerges as a significant concern for interviewees 3 and 9, indicating the considerable investment required for DT development and implementation. Technological hesitancy, particularly related to cultural resistance, is also a recurring issue. Interviewee 11, however, identifies challenges more unique to their context, such as difficulties in combining diverse data sources and the lack of clear business models. Regulatory challenges and the need for standardization of data are also prominent concerns, underscoring the complexity of aligning innovative technologies with existing legal frameworks and industry standards.

Across the three archetypes, several similarities and differences emerge in the experiences of early adopters. Financial capacity and the lack of clear business models are recurring challenges across all archetypes, highlighting a common struggle to justify and sustain the economic viability of digital twins. Standardization of data is another shared concern, reflecting the industry's need for consistent and interoperable data formats to ensure the effective integration and operation of DTs. However, the challenges related to data ownership, regulatory compliance, and technological hesitancy vary significantly between the archetypes and even within them, depending on the specific focus and stage of DT adoption. For instance, while data ownership is a concern in Archetypes 1 and 2, it is less prominent in Archetype 3, where the focus shifts more toward the integration of advanced technologies like AI and IoT. These differences underscore the varying levels of maturity and focus among companies adopting DTs, with each archetype facing a unique set of challenges that reflect their specific operational contexts and strategic priorities.

Potential adopters vs Archetype

	Pre-Build	Construction	USE	End of Life
Slow	AT 1 Int. 10		AT 1 Int. 5; AT 1 Int. 10	AT 1 Int. 10
Narrow	AT 1 Int. 10		AT 1 Int. 5; AT 1 Int. 10	AT 1 Int. 10
Close	AT 1 Int. 10		AT 1 Int. 5; AT 1 Int. 10	AT 1 Int. 10
Regenerate	AT 1 Int. 10		AT 1 Int. 5; AT 1 Int. 10	AT 1 Int. 10

Figure 16: Archetype 1 preference potential adopters compared to matrix positions

Potential adopters of Digital Twins (DTs) within Archetype 1 (AT1) exhibit a preference for this archetype primarily due to its adaptability and simplicity, making it suitable for applications where material lifecycles are shorter or where foundational platforms are needed. For instance, Interviewee 5, representing an interior design branch of a large international firm, values AT1's capability to support circularity strategies like Regenerate and Slow. This involves designing for disassembly and using biobased materials to extend building lifespans. The firm's focus on the pre-build and use phases, where material flows are frequent, aligns well with AT1's straightforward integration potential. Similarly, Interviewee 10, a researcher in a construction-focused institution, favours AT1 due to its flexibility in building a digital twin from the ground up. This allows the institution to gather and store comprehensive data across various lifecycle phases, which is essential for advancing their research into sustainable practices. However, both interviewees anticipate significant barriers to adoption. Interviewee 5 is concerned with financial capacity, data standardization, and cultural resistance, highlighting the difficulties in securing resources and ensuring consistent data management. In contrast, Interviewee 10 expects challenges related to data ownership, regulatory compliance, and the lack of clear business models, indicating a broader concern over control, governance, and the economic viability of DT implementation.

	Pre-Build	Construction	USE	End of Life
Slow	AT 5 Int. 4; AT 5 Int. 7; AT 5 Int. 12	AT 5 Int. 4	AT 5 Int. 4; AT 5 Int. 7; AT 5 Int. 12	AT 5 Int. 4; AT 5 Int. 7; AT 5 Int. 12
Narrow	AT 5 Int. 4; AT 5 Int. 7; AT 5 Int. 12	AT 5 Int. 4	AT 5 Int. 4; AT 5 Int. 7; AT 5 Int. 12	AT 5 Int. 4; AT 5 Int. 7; AT 5 Int. 12
Close	AT 5 Int. 4; AT 5 Int. 7; AT 5 Int. 12	AT 5 Int. 4	AT 5 Int. 4; AT 5 Int. 7; AT 5 Int. 12	AT 5 Int. 4; AT 5 Int. 7; AT 5 Int. 12
Regenerate	AT 5 Int. 4; AT 5 Int. 7; AT 5 Int. 12	AT 5 Int. 4	AT 5 Int. 4; AT 5 Int. 7; AT 5 Int. 12	AT 5 Int. 4; AT 5 Int. 7; AT 5 Int. 12

Figure 17: Archetype 5 preference potential adopters compared to matrix positions

Archetype 5 (AT5) is preferred by organizations that require more sophisticated digital twin capabilities, particularly those involved in managing complex data across multiple lifecycle phases. For example, Interviewee 4, leading a circular team in an engineering firm, emphasizes the need for AT5's high-fidelity DT to manage detailed data throughout the material lifecycle. This archetype supports their work in material inventorying and reuse, which are critical for their focus on Regenerate and Close strategies, primarily during the end-of-life phase. Interviewee 7, a building physics and sustainability consultant, also favours AT5 due to its advanced data integration capabilities, which are crucial for optimizing material management and achieving sustainability goals. This preference is echoed by Interviewee 12, a senior sustainability advisor, who highlights AT5's AI-driven insights and ability to manage complex data across different phases as essential for providing holistic sustainability advice. However, the barriers faced by potential AT5 adopters are substantial and diverse. Financial capacity is a common concern among Interviewees 4 and 12, reflecting the significant investment required for DT implementation. Regulatory barriers are also prominent, with both interviewees worried about potential legal and compliance issues. Additionally, Interviewee 12 points to challenges related to data ownership and the lack of clear business models, similar to the concerns expressed by AT1 adopters. The need for data standardization is also emphasized by Interviewees 4 and 7, underscoring the importance of consistent data formats in ensuring interoperability within the advanced DT systems required by AT5.

Despite the differences in their organizational contexts and the complexity of their circularity strategies, potential adopters of AT1 and AT5 share several common challenges. Both archetypes face significant financial constraints, with organizations across both groups expressing concerns about the financial resources required to implement and sustain DTs. Additionally, technological hesitancy, particularly cultural resistance to new technology, is a barrier that spans both archetypes, though it appears more pronounced in the context of AT5, where the technological demands are greater. However, the specific challenges related to data management and regulatory compliance diverge between the two archetypes. AT1 adopters are more concerned with basic data standardization and governance, reflecting their need for a flexible and straightforward DT platform. In contrast, AT5 adopters grapple with more advanced issues like data ownership and the integration of complex data systems, which are necessary for their high-fidelity DT applications. These differences highlight the varying levels of sophistication and focus required by different organizations, with AT1 adopters prioritizing ease of integration and foundational data management, while AT5 adopters focus on advanced data handling and regulatory compliance to support their intricate circularity and sustainability goals.

Across both the potential users and early adopters non mentioned the lack of market parties capable of creating digital twins for use in the circular built economy. Data Safety and Data privacy were both mentioned by only 2 early adopters both of which used AT1. Both were very different organization; Data safety issue was encountered as an issue by interviewee 6 that created a platform for hosting information from other organizations while the matter of data privacy was encountered by a company that needed to monitor the health of structures throughout their use phase. Both companies were active across life cycle multiple stages and required long term data acquisition or storage. This could explain their encounters with these issues in the domain of data-oriented challenges. It should be noted that the majority of issues in the domain of data were not mentioned as barriers. With the exception of standardization and ownership of data the others (DWSS, Data Safety and Data privacy) were not mentioned. These should however not be discounted as all early adopters regardless of AT preference and position in the circularity matrix.

6.4.2 Barriers, Challenges and Archetype

In this paragraph the intersection between archetypes and barriers and challenges will be discussed to see whether patterns emerge and whether these could be explained.

	DT used		
Interviewees	intv. 6, 8 & 13	intv. 1 & 2	intv. 3, 9 & 11
Combining Data (DWSS)	1	1	1
Data Ownership	1	1	1
Data Privacy	1	0	0
Data Safety	1	0	0
Financial Capacity	2	2	2
Lack of Clear Business Models	3	1	1
Lack of Parties Capable of Making DT's	0	0	0
Regulatory challenges	1	1	2
Standardization of data	2	2	2
Technological Hesitancy (cultural)	2	1	2
Archetype Choice	AT 1	AT 2	AT 3

Table 8: comparison Archetype choice and experienced challenges

The challenges associated with Digital Twin (DT) adoption vary not only in type but also in frequency across the three archetypes (AT 1, AT 2, and AT 3), with the number of interviewees considered. **AT 1**, represented by interviewees 6, 8, and 13, encounters a significantly higher frequency of challenges related to the **lack of clear business models** (three instances), which is notably more than the single instance reported by the interviewees of **AT 2** (1 and 2) and **AT 3** (3, 9, and 11). This suggests that AT 1 adopters, despite having more interviewees, struggle more acutely with defining and sustaining viable economic frameworks for DT deployment. Additionally, **data privacy** and **data safety** challenges are exclusively reported by AT 1, indicating unique concerns in this group that are not present in AT 2 and AT 3. On the other hand, **financial capacity** and **standardization of data** emerge as universal challenges across all archetypes, each reported twice, reflecting widespread concerns regardless of the number of interviewees. **Regulatory challenges** are more prominent in **AT 3** with two instances, compared to just one in the other archetypes, indicating a higher sensitivity to compliance and legal frameworks among AT 3 adopters. **Technological hesitancy**, although present across all archetypes, is reported twice by interviewees in AT 1 and AT 3, highlighting a greater cultural resistance to DT implementation in these groups. This analysis underscores that while some challenges are consistently experienced across archetypes, others are more specific to certain groups, influenced by the number of interviewees and their unique contexts in adopting DT technology.

When considering the prevalence of lack of clear business models and data privacy and safety issues in relation to AT1, it could be considered that these are challenges related to maturity. By this is meant that AT1 could be considered an entry point in to the adoption of digital twins more broadly and creating a business case and consideration of data privacy and security could be seen as necessary but complex consideration that need to be solved for initial adoption. It should be stated that this consideration is only true if AT1 in practice is the entry point for organization into a digital twin supported CBE. Financial constraints and Standardization of data were challenges named by all archetypes reported by early adopters. When considering the archetypes as a progression in maturity it could be stated that these challenges remain a constant that should be taken into consideration when deciding to implement digital twins. This also seems to be true for cultural hesitancy.

However, the regulatory challenges also seem to be a constant but with less frequency in AT 1 and AT 2. The data set however would perhaps provide clearer patterns if it was expanded.

	DT wanted	
Interviewees	intv. 5 & 10	intv. 4, 7 & 12
Combining Data (DWSS)	0	0
Data Ownership	1	1
Data Privacy	0	0
Data Safety	0	0
Financial Capacity	1	2
Lack of Clear Business Models	1	1
Lack of Parties Capable of Making DT's	0	0
Regulatory challenges	1	2
Standardization of data	1	2
Technological Hesitancy (cultural)	1	3
Archetype Choice	AT 1	AT 5

Table9: comparison Archetype anticipated challenges and archetype preference

The perceived barriers to adopting Digital Twins (DT) vary between archetype AT 1 and AT 5, with the number of interviewees highlighting different challenges. **AT 1**, represented by interviewees 5 and 10, perceived barriers across a broader spectrum but with less frequency. Specifically, **data ownership, financial capacity, lack of clear business models, regulatory challenges, standardization of data, and technological hesitancy** are each mentioned **once,** suggesting a uniform but less intense distribution of barriers, however when considering individual interviewees it is still spread out. In contrast, AT 5, represented by interviewees 4, 7, and 12, faces a more concentrated set of barriers, with financial capacity, regulatory challenges, and standardization of data each encountered twice. The most significant barrier for AT 5, however, is technological hesitancy, mentioned three times, indicating a substantial cultural resistance within this archetype to the adoption of DTs. Although both archetypes share common barriers such as data ownership and lack of clear business models, AT 5 interviewees perceive financial and regulatory issues, along with cultural resistance, as more pronounced obstacles compared to AT 1. This suggests that while both groups are cautious, AT 5 users may perceive more significant hurdles in these specific areas, reflecting the complex nature of adopting DT technology across different contexts.

This was then extrapolated to digital twins that take into account the use cases resulting in Archetypes. This took into account the dimensions data collection, data handling and distribution, and conceptual scope. We derived the meta-dimensions inductively based on the dimensions' perceived similarity to each other. Combining this with the different sub technologies mentioned combining these with a technical perspective of digital twins that focus on sub technologies mentioned earlier, resulted in a definition of digital twins but also variations on this. Resulting in digital twins being used in this thesis as a network of technologies created and supported by a network of differing sub technologies, with a variety of configurations based on the use case.

When considering the last aspect of the thesis the question was answered what are the experienced and anticipated barriers and challenges for use of digital Twins?

As stated previously 62% of Interviewees actually already used a digital Twins to support their circular activities. This was more than anticipated. Of these the challenges experienced by 75% of them were issues with standardization of practices and processes, and lack of financial capacity. Over 50% of them mentioned challenges with technological Hesitancy, technological immaturity, and regulatory challenges. More than a third mentioned Challenges with combining data, challenges stemming from data ownership, lack of a clear business model for use.

However, these barriers were not as previously thought separate and individual aspects. However, they still employed these technologies by employ some of the following solutions. It Should however be stated that solutions mentioned are not meant to address all challenges as some were not resolved and are still a challenging factor but not a barrier to use. The following solutions were mentioned: Leadership in communication and BIM protocols is crucial for effective collaboration, alongside standardizing software to improve interoperability. Continuous technological improvements, such as material reuse and effective labelling, are prioritized, along with stringent quality requirements to maintain high standards. Projects are organized and financed independently to ensure control and flexibility, and partners are carefully selected and screened for alignment with project goals. All parties are required to conform to established BIM protocols or provide viable alternatives. Collaborative innovation and knowledge sharing with research institutes foster incremental improvements. Developing modular and scalable solutions facilitates adaptation and growth, while using open standards like IFC ensures interoperability. Creating ontologies standardizes digital twins and enhances system compatibility. Efficient data management and standardization are enforced through rules and queries, supporting technological growth with necessary infrastructure. Strategies are adapted for larger portfolios to increase financial viability. Sustainability goals and regulatory compliance drive project innovation, incentivizing circular economy practices and digital twins through market demand or regulations. Scanning technologies gather detailed data while protecting privacy and change management strategies ensure effective integration of new technologies. Customer-centric innovations ensure that new technologies add value, improving business cases and promoting adoption.

Barriers were mentioned 38% of interviewees which did not use Digital Twin Technologies to support their circular activities. 60% of respondent mentioned barriers relate directly to lack of financial to create or use these, regulatory issues, standardization of processes, practices and formats and technological hesitancy. Data ownership (i.e. spread ownership of data and willingness to share and lack of a clear business model were mentioned by 40% of potential users.

Notable was that the challenges related to combining different data types was not present as barriers for potential users. This could potentially be due to the fact that it is a technical aspect which would become evident during the process of implementing the technologies and having to merge a variety of data streams to create a coherent picture.

Notable too was that the challenge of technological immaturity was not mentioned by early adopters but was significant among potential users as a barrier. This a possible result of potential users not being well versed enough in the technology. It should be stated that the interviewees that already adopted digital twins noted that the technology was that and has been there for a while. Even if it's not yet sufficiently user friendly, it's still capable of being used to support their circular activities.

In with both potential users and early adopters, roughly 40% of interviewees mentioned the ownership of data as an issue, both mentioned data scarcity as a factor of spread data ownership and willingness to share data. More than 60% was mentioned by both groups as financial capacity for both development and acquirement was mentioned by both groups. Roughly 40% of both groups also mentioned lack of a clear business model stemming from unclear benefits for both all stakeholders in the process. Regulatory challenges and challenges were once again mentioned by both groups, with 50 % of early adopters and 60% of users mentioning this factor. This stems from regulation being an inhibiting factor as it does not take into account the data produced and stored in digital twins thus lessening the incentives for stake holders and inhibiting full use of capabilities. 75% of early adopters and 60% of potential adopters mentioned the standardization of process, method and formats as an issue. Even though the technical understanding of early adopters was more expanded the potential users also recognized this as a barrier, as it primarily stemmed from the need for collaboration with external parties. Cultural Hesitancy was also mentioned by both with both mentioning cultural hesitancy withing the construction industry, also within their own organizations, and without the industry among.

6.4.3 Digital Twins and the CBE

Digital Twin Facilitating CBE involves addressing the issue of generic archetypes being unsuitable for both technologies and companies. This creates a Catch 22 situation where the CBE economy does not yet exist, making it difficult to establish DCBE. It's a chicken and egg scenario. DCBE, or Digital Circular Business Economy, is a crucial factor in achieving circularity. It plays a significant role in overcoming barriers and challenges related to the implementation of digital twin functions in circular systems.

Regarding digital models. The Technology and Tools grouping encompasses the practical steps taken to incorporate and enhance digital twin technology in current systems. Potential remedies encompass leveraging augmented IFC models and mobile technology to collect data on-site, alongside with a methodical approach for certain situations. These efforts emphasise the vital importance of technology in enhancing the efficiency and effectiveness of circular processes. The primary focus of Financial Incentives and Business Models is on the economic aspects of utilising digital twin technology. This entails the creation of systems of rewards, business rationales, and regulatory frameworks that encourage the adoption and advancement of benefits derived from digital twins. The interviewees stressed the significance of incorporating financial methods with circular objectives to attain sustainable and profitable outcomes. The significance of Stakeholder Engagement and Change Management resides in the imperative for strategic communication and education to facilitate the adoption and execution of digital twins. The solutions in this category emphasise the importance of including both internal and external stakeholders in the process of transitioning to digitisation. They also stress the importance of the sector adopting a new attitude that fully embraces evolving technologies. The Regulatory and Legal Aspects area specifically addresses the external considerations that influence the application of digital twin technology. Government regulations, concerns regarding data protection, and the development of legal contracts are acknowledged as pivotal elements that might either support or hinder the integration of digital twins in circular operations.

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6.5 Hypothesis

In this chapter the hypothesis will be reviewed by testing it against the results and the discussion. The hypothesis established in the introduction was that *the circularity techniques employed by a corporation are determined by its special needs, which subsequently influence the desire or perceived necessity for digital twins with certain characteristics. This in turn dictates the barrier or challenges that are related to the implementation of Digital Twin technologies for circularity purposes*.

The relationship between a company's circularity strategy and its choice of digital twin technology is often perceived as linear, with the assumption that the strategic goals directly inform the selection of digital twin configurations, which in turn dictate the barriers and challenges encountered. However, this perspective may oversimplify the complexities inherent in the adoption of digital twin technologies within the circular built environment.

The first aspect, the direct link between circularity strategy and archetype choice was somewhat established as there was in both generic descriptions and specific circular strategies plausible links highlighted in previous chapters. Again, the correlation established only possible causal reasoning was given, this was due to a clear need for wider data sets perhaps focused on more clear subsets of the circularity matrix.

The second link was the possible generation of barriers and challenges being a factor of each archetypes configuration and requirements. The correlation could be somewhat observed but for more definitive conclusions would be necessary to expand the number of interviews.

Based on these two factors it could be stated that while it is true that a company's circularity objectives can shape its technological needs, the interplay between strategy, technology selection, and the resulting challenges is not always straightforward.

Other factors such as organizational readiness, external market conditions, and evolving technological landscapes may also play critical roles in this dynamic, suggesting that the relationship between strategy, digital twin selection, and the associated challenges might be more nuanced than initially assumed. Additionally, it should perhaps be considered that organizations position in the circularity matrix could be researched further to establish patterns within it based on more generic organizational description.

6.6 Literature Comparison

In this chapter a comparison to the literature review will be discussed. As illustrated by the way this research was conducted there was a gap in the literature that this thesis wanted to fill in. In this way the analysis and research conducted in this thesis was based on previous research, using it to generate both tools for categorizing and understanding the main concepts of this thesis. However, a discussion can still be conducted on the grounds of how the concepts discussed in the literature review differ from the interview results. This chapter will also highlight whether the barriers and challenges identified in their description are unique compared to the generic barriers and challenges identified during the literature review.

6.6.1 What was added

In the Introduction the European Commision (2018), was quote as stating that the Construction industry, was one of the most linear. However, this thesis has its start in the circular built environment. The Circularity matrix was created by combining a model of the built environment created by Hürlimann, Smith, Johnson, & Lee, (2022) and the categorization of circularity strategies that Bocken et al., (2020) based on a literature review. By creating a matrix that combines the model of the built environment in which the sectors and actors were translated to phases. The translation into pre-build, construction, use, and end-of-life phases illustrates the alignment of specific sectors and actors with each stage of the built environment's life cycle.

During the pre-build phase, activities such as change initiation, strategic planning, and project initiation correspond to high-level decision-making processes, involving urban planners, engineers, and property developers, who establish the socio-economic, environmental, and regulatory frameworks for the project. Strategic planning also engages urban designers, landscape engineers, and owners/investors to develop formal tools, zoning regulations, and infrastructural blueprints essential for initiating projects.

The **construction phase** sees the transition from planning to the physical realization of the project. Here, the key stakeholders such as **construction managers**, **property developers**, and **landscape engineers** take over, focusing on production, infrastructure development, and handing over the built form to private or public entities. These actors, supported by **engineers** and **allied professionals**, are responsible for executing the designs within the planned parameters.

In the **use and ongoing management phase**, the focus shifts to maintaining and adapting the built environment to meet the evolving needs of the population. This phase involves **property managers**, **urban planners**, and **designers** who engage in continual maintenance, renovations, and repairs, ensuring that the built form remains functional and sustainable. **Owners/investors** play a significant role in strategic decision-making during this phase.

Lastly, the **end-of-life phase** involves the decommissioning or renewal of buildings and infrastructure. **Urban planners**, **property developers**, and **engineers** are key actors in identifying future trends, planning for renewal, and recovering reusable components before decommissioning. The involvement of **property advisors** and **managers** ensures that the process is economically and environmentally sustainable, aligning with broader circular economy goals. Each phase showcases a dynamic interplay between various stakeholders, emphasizing their unique roles across the lifecycle of the built environment.

Several interviewees highlighted that organizations do not always fit neatly into a single phase of the built environment lifecycle, and their roles often span multiple stages. As demonstrated by certain respondents, organizations frequently operate across different phases, such as planning, construction, and ongoing management, blurring traditional boundaries. For example, a company might be involved in both the **design** and **construction** phases while simultaneously engaging in strategic planning or post-construction management. Furthermore, organizations can take on multiple roles, acting as **developers**, **managers**, and even **designers** depending on the project's requirements. This fluid configuration challenges the notion of distinct phases and specialized actors, suggesting that the evolving complexity of projects often requires organizations to adapt and assume diverse responsibilities across the lifecycle. As a result, the linear segmentation of phases is not always reflective of the dynamic reality in practice, where organizational roles are flexible and highly situational, adapting to the demands of the project and the broader built environment.

6.6.2 Matrix

In regard to the matrix no new specific strategies appeared to be identified however the strategies and sub strategies were aligned with the phases of the building's life cycle. This was this thesis's contribution is the creation of an overview that cross-referenced the strategies identified by Bokken et. Al, (2020) with the phases in which they could possibly be employed. This corresponds a specific actor and sector. This combination creates a common taxonomy tool according to which organizations can identify themselves. Even though the original purpose was meant create focus by correlating one section of the matrix for each organization type, the small data set and fluidity of organizations discussed earlier means that the taxonomy purpose is the main benefit to this thesis. As stated in previous sections patterns might become clearer that in this discussion when larger data sets are formed.

6.6.3 Digital Twin description

In regard to the concept of digital twins this thesis codifies the definitions of digital twins as networks of different technologies. It illustrates that the concept of a digital twin benefits from considering it not only as firmware or a file. By considering a digital twin in its configurations based on the application of the technology we see that the archetypes generated can provide a clearer description than a generic one. Despite not exclusively focusing on digital twins Sultan Cetin et. al, (2022) provide two essential components that formed the way this thesis sees digital twins by framing a digital circular environment through analysis of multiple technologies. Firstly, Digital twins for a specific circular purpose and with a specific actor in mind. And secondly the underlying networks of technologies. For this thesis however the methodology used in this thesis allowed for a broader and more interviewee generated result. This thesis in contrast to the previous paper incorporated the fact that within the circular built environment there are a variety of actors that execute a variety of differing circularity strategies in a variety of phases. This thesis combined the two concepts named with the idea of archetypes describes by van der Valk et. al, (2022) by providing generic digital twin archetypes with the networks of technologies described and allowing for variety of interviewees themselves to link them and their capabilities to their specific circularity strategies. Thus, combining and adding to both of these essential resources.

6.6.4 Barriers and challenges literature vs results

In both sections, the barriers and challenges to the adoption and implementation of digital twins are critically examined, yet with a distinct difference in focus. The obstacles to digital twin implementation section emphasizes a general, literature-based perspective, highlighting key obstacles such as safeguarding data, lack of standardized data standards, and financial constraints. Issues related to data privacy, cybersecurity, and ownership are central to these challenges, where ensuring appropriate access and securing sensitive information are significant concerns (Adams, 2019; Shao & Helu, 2020). These challenges are compounded by the absence of agreed-upon protocols and the need for interoperable systems, which hinder seamless data exchange and operational efficiency (Rasheed et al., 2020; Qi & Tao, 2018). Moreover, financial and economic hurdles, particularly the lack of standardized business models and high implementation costs, make digital twin technology unattractive to many organizations (Cetin et al., 2022).

In contrast, the barriers and challenges results section delves deeper into specific challenges derived from user experience and interviews, offering a more nuanced categorization of the barriers and challenges. For example, safeguarding and ownership are divided into subcategories of data privacy, cybersecurity, and ownership. Even though these were named by Cetin et al., (2022) they were not translated to the experience of a broad selection of interviewees. Likewise, the lack of standardized data standards and tools is refined into discussions on diverse data types and their integration into coherent systems. Economic barriers are similarly disaggregated into financial capacity, the availability of capable market partners, and the absence of a clear business model (Cetin et al., 2022). Cultural challenges are also specifically highlighted in the barriers and challenges results section, where technological hesitancy in the building industry poses a significant barrier to the adoption of digital twins, as organizations prefer familiar methods over new technologies (Cetin et al., 2022). Furthermore, regulatory challenges are underscored by the lack of legal frameworks and standards, which stymie broader adoption (Cetin et al., 2022).

While both sections acknowledge the key barriers, The barriers and challenges results section offer a more detailed analysis based on user experience, presenting refined subcategories that offer greater specificity than the broader issues discussed in the obstacles to digital twin implementation section. This contrast highlights the importance of empirical user feedback in understanding and addressing the nuanced barriers to digital twin adoption.

6.7 Conclusion

This concluding chapter synthesizes the key findings of the research and reflects on the main objectives outlined in the introduction. The aim of this thesis was to explore *What are the observed and anticipate barriers and challenges for early and potential adopters of Digital Twins technologies in the Dutch circular-built environment?* with a focus on Circularity Strategies, Digital Twins, Early- & Potential adopters and experienced challenges and anticipated barriers. Over the course of this study, several important insights have emerged that contribute to a deeper understanding of the factors that influence the adoption of digital twins for circularity purposes, particularly in relation to use of specific archetypes by specific types of circularity oriented organizations. The discussion and result sections of this thesis will be referred to in order to answer the research question and the supporting sub questions.

In this chapter, will first provide a concise summary of the primary findings across the core areas of investigation. Additionally, this thesis will address the limitations of the study and propose several avenues for future research in the last few sections. Finally, this chapter will conclude with a reflection on the significance of the study, emphasizing its contribution to the field and its potential impact on future developments.

The ***Research Question*** at the beginning of the thesis was:

What are the observed and anticipate barriers and challenges for early and potential adopters of Digital Twins technologies in the Dutch circular-built environment?

To answer this, we firstly focused on answering the sub questions.

The Circular Built Environment

The first sub question was "How is circular construction implemented in the Netherlands?".

The definition of the built environment as defined in chapter 4.1 was a holistic interpretation of the concept. The definition relevant for this thesis was based on the study by Bartuka's (2007), which stated that **the built environment consisted of products and structures are part of a larger network that makes up the built environment.** Meaning the consideration of products and structures that are made by and for humans to facilitate them in their activities, as a sub section of the larger context of the non-built environments. The structure of the built environment in this thesis as mentioned in chapter 4.2. is based on the activities that take place in order to generate it, meaning the activities throughout the lifecycle of structures and their components. This was used further in the research. The structure of the built environment was thus stated to consist of the change initiation section, the strategic planning section, the project consideration and initiation section, the design section, the costing approval section, the construction section, the use and management section and lastly the renewal, recovery and decommissioning section. The structure encompasses the process in which the aforementioned structures are created and the products that are part of the process are used. In addition, in the relevant chapter the actors active in these sections can also be found.

The definition of the Circularity used in this thesis that encompasses several different definitions of circularity in the built environment specifically. It should be noted that it appears that definitions of circularity are often linked to the method of its implementation. Based on the sources consulted the definition of **circularity in the Built Environment is the application of method and strategies to reach a more circular construction process that exhibits at least one of the following characteristics namely optimized use of resources in the creation and provision of products and structures, Recirculating of resources within the production cycle, Regenerative properties incorporated into products and structures, extension of product and structure life cycles.** The Matrix found in chapter 4.2.3 synthesises the definition of both the built environment and the circular built environment provided in this thesis and merges this with the phases of the identified. By merging the strategies of circularity and the phases of the built environment a tool was created as for a common taxonomy between interviewer and interviewee.

The barriers to circularity in the built environment were gathered, this was necessary to distinguish between barriers to digital twin implementations and circularity barriers. These barriers were organized in several tables that were discussed in the literature chapter and can be found in the **appendix.** The barriers were Cultural, Market, Knowledge, Financial, Management, Regulatory, Technological, Supply Chain and environmental.

As stated in previous chapters the Circularity in the built environment is a growing concept addressing environmental and social challenges. It involves reducing, reusing, and recycling materials, resources, and waste. This approach emphasizes systemic engagement, stakeholder engagement, and renewable resource use. Key sectors include planning, construction, use and end of life.

Digital Twins

The second sub question was what are "What are Digital Twins for the Circular Built environment?". The Section regarding the definition of Digital Twins concluded that digital twins were a broad concept with different interpretations but that for the purpose of this thesis **digital twins were network of technologies that produced a digital replication of a structure that reflected reality to a certain degree**. This was based on the literature review by van der Valk, et. Al (2022) in which they discuss the various iterations of digital twins, which connect actual and virtual items. However, definitions vary by use scenario, with healthcare requiring different qualities than manufacturing. Real world data inputs are a shared factor amongst digital twins. It should be noted that Digital Twins could be created before the actual structure is built but to make it a twin the cross-referencing reality with the virtual twin is necessary and the resolution of discrepancies is necessary. **For this thesis a combined perspective on the definition is be given that considers the physical network and the software components to provide a holistic description of a digital twins**. Based on this a definition was chosen that focusses on a virtual representation that integrates data inputs, handles and processes data, and establishes a data linkage between the virtual and physical worlds. Synchronization is crucial to reflect changes in the physical object's state. However, there are instances where digital twins lack automatic data flow. Despite this, everyone agrees that a digital twin is a representation of a physical asset that reflects a physical entity and must be associated with the physical part to adapt to its changes.

This was then extrapolated to digital twins that take into account the use cases resulting in Archetypes. This took into account the dimensions data collection, data handling and distribution, and conceptual scope. We derived the meta-dimensions inductively based on the dimensions' perceived similarity to each other. Combining this with the different sub technologies mentioned combining these with a technical perspective of digital twins that focus on sub technologies mentioned earlier, resulted in a definition of digital twins but also variations on this. The archetypes were the Design and repository twin, the basic analysis twin, the predictive analysis twin, the AI automated twin and the advanced high-fidelity twin.

The sub question “What are the experienced and anticipated barriers and challenges for use of digital Twins?” was answered by conducting the interviews. The answer this question was synthesized in the following two sections.

Early adopters

As stated previously 8 of

the Interviewees actually already used a digital Twins to support their circular activities and 5 did not. This was more than anticipated. 6 of the early adopters reported challenges experienced that could be categorized as standardization of practices and processes, and lack of financial capacity challenges. 5 of them mentioned challenges with technological Hesitancy, lack of a clear business model for use, technological immaturity, and regulatory challenges , 4 mentioned regulatory challenges and 3 mentioned Challenges with combining data, challenges stemming from data ownership. The remaining challenges were mentioned by 1 or none of the early adopters.

However, these barriers were not as previously thought separate and individual aspects. However, they still employed these technologies by employing some of the following solutions. It Should however be stated that solutions mentioned are not meant to address all challenges as some were not resolved and are still a challenging factor but not a barrier to use. The following solutions were mentioned: Leadership in communication and BIM protocols is crucial for effective collaboration, alongside standardizing software to improve interoperability. Continuous technological improvements, such as material reuse and effective labelling, are prioritized, along with stringent quality requirements to maintain high standards. Projects are organized and financed independently to ensure control and flexibility, and partners are carefully selected and screened for alignment with project goals. All parties are required to conform to established BIM protocols or provide viable alternatives. Collaborative innovation and knowledge sharing with research institutes foster incremental improvements. Developing modular and scalable solutions facilitates adaptation and growth, while using open standards like IFC ensures interoperability. Creating ontologies standardizes digital twins and enhances system compatibility. Efficient data management and standardization are enforced through rules and queries, supporting technological growth with necessary infrastructure. Strategies are adapted for larger portfolios to increase financial viability. Sustainability goals and regulatory compliance drive project innovation, incentivizing circular economy practices and digital twins through market demand or regulations. Scanning technologies gather detailed data while protecting privacy and change management strategies ensure effective integration of new technologies. Customer-centric innovations ensure that new technologies add value, improving business cases and promoting adoption.

Potential Adopters

Barriers were mentioned the 5 interviewees that did not use Digital Twin Technologies to support their circular activities. 3 of the respondents mentioned barriers relate directly to lack of financial to create or use these, regulatory issues, standardization of processes, practices and formats and 4 mentioned technological hesitancy. Data ownership (i.e. spread ownership of data and willingness to share) and lack of a clear business model were mentioned by 2 of the potential users.

Notable was that the challenges related to combining different data types was not present as barriers for potential users. This could potentially be due to the fact that it is a technical aspect which would become evident during the process of implementing the technologies and having to merge a variety of data streams to create a coherent picture.

Notable too was that the challenge of technological immaturity was not mentioned by early adopters but was significant among potential users as a barrier. This a possible result of potential users not being well versed enough in the technology. It should be stated that the interviewees that already adopted digital twins noted that the technology was that and has been there for a while. Even if it's not yet sufficiently user friendly, it's still capable of being used to support their circular activities.

Potential and Early Adopter comparison

Here a summary of the discussion on the comparison between early and potential adopters is given. This is done in percentages as to compare the two despite different sample sizes. In with both potential users and early adopters, roughly 40% of interviewees mentioned the ownership of data as an issue, both mentioned data scarcity as a factor of spread data ownership and willingness to share data. More than 60% was mentioned by both groups as financial capacity for both development and acquirement was mentioned by both groups. Roughly 40% of both groups also mentioned lack of a clear business model stemming from unclear benefits for both all stakeholders in the process. Regulatory challenges and challenges were once again mentioned by both groups, with 50 % of early adopters and 60% of users mentioning this factor. This stems from regulation being an inhibiting factor as it does not take into account the data produced and stored in digital twins thus lessening the incentives for stake holders and inhibiting full use of capabilities. 75% of early adopters and 60% of potential adopters mentioned the standardization of process, method and formats as an issue. Even though the technical understanding of early adopters was more expanded the potential users also recognized this as a barrier, as it primarily stemmed from the need for collaboration with external parties. Cultural Hesitancy was also mentioned by both with both mentioning cultural hesitancy withing the construction industry, also within their own organizations, and without the industry among. The lack of market parties capable of creating digital twins for the circular built economy was not mentioned by potential users and early adopters. Data safety and privacy were mentioned by only two early adopters, both using AT1. Both companies were active across life cycle multiple stages and required long-term data acquisition or storage. However, most data-oriented challenges were not mentioned as barriers, except for standardization and ownership of data. The other issues (DWSS, Data Safety, and Data privacy) were not mentioned. These should not be discounted as all early adopters, regardless of AT preference and position in the circularity matrix, face data-oriented challenges.

The last sub question was "What are the employed and possible solutions for the experienced challenges and how do these overlap with barriers?".

Solutions

The key findings from the discussion on the adoption and integration of Digital Twin technologies in the built environment. Based on the discussion, it is evident that implementing Digital Twins involves a multifaceted set of challenges, including data standardization, financial constraints, cultural hesitancy, and regulatory issues. That chapter evaluated various proposed solutions aimed at overcoming these barriers, assessing their effectiveness and identifying gaps where challenges remain unresolved.

Data standards and integration are critical for harmonizing diverse data sources within Digital Twin ecosystems. Proposed solutions include establishing communication and data-sharing protocols, expanding existing standards like Industry Foundation Classes (IFC), and creating unified data structures to manage sustainability efforts. These initiatives address the lack of standardized data tools and the diversity within source systems by reducing fragmentation and improving integration

The discussion highlights the importance of continuous technological integration and iterative improvement to overcome hesitancy in adopting Digital Twins. Solutions include new technology integration, enhancing existing tools, and connecting lifecycle services within Digital Twins.

The establishment of financial incentives and clear business models is essential for driving Digital Twin adoption. Proposed solutions focus on aligning financial incentives with customer demands and creating value-driven business cases. Although these measures address some financial barriers, they do not fully resolve the underlying issue of limited financial capacity, particularly for smaller organizations.

Effective stakeholder engagement and change management strategies are crucial for overcoming cultural resistance to new technologies. Proposed solutions include selecting innovation-friendly partners and educating stakeholders on the benefits of Digital Twins. These strategies foster a positive attitude towards technology adoption but do not address more systemic issues.

Creating robust regulatory and legal frameworks is vital for ensuring the secure and standardized use of Digital Twins. Proposed solutions include developing regulations to enforce standards, ensuring data privacy, and establishing legal agreements. While these measures tackle some regulatory challenges.

Despite the proposed solutions, several key challenges remain unresolved, including data ownership, data privacy, financial capacity, and the availability of capable market partners. Addressing these gaps will be crucial for achieving the successful and widespread adoption of Digital Twin technologies. The analysis shows that while significant strides have been made, further research and strategic initiatives are necessary to fill these gaps and fully leverage the potential of Digital Twins in creating sustainable and circular built environments.

The solutions discussed effectively address some of the core challenges related to data standardization, technological integration, and financial incentives. However, persistent barriers—such as unresolved issues of data ownership, insufficient cybersecurity measures, and financial constraints—highlight the need for ongoing efforts to overcome these obstacles. Future research should focus on addressing these unresolved challenges to facilitate the broader implementation of Digital Twin technologies in the built environment.

6.8 Recommendations

This chapter presents a set of recommendations based on the research findings concerning the barriers and challenges faced by early and potential adopters of Digital Twin (DT) technologies within the Dutch circular-built environment. The recommendations are informed by the observed complexities and diverse experiences of the interviewees, and they aim to provide actionable insights for both practitioners and future researchers in this domain.
Collaboration between various stakeholders is critical to overcoming the barriers associated with adopting Digital Twin technologies. It is crucial to establish a collaborative environment where knowledge and resources are shared because DT implementations are interdisciplinary and frequently involve urban planners, engineers, architects, property developers, and IT specialists. To guarantee a comprehensive approach to DT adoption, this may entail forming working groups or collaborative platforms that unite specialists from various fields. Organisations can more successfully manage the difficulties of DT integration and overcome obstacles by encouraging cooperation and communication amongst these varied stakeholders.

Off-the-shelf technologies can provide a more accessible entry point for organisations that are reluctant to adopt Digital Twins because of perceived technical complexity or cost. These technologies offer pre-configured solutions that require little modification, which makes them a great place for businesses just getting started with DTs to start. Organisations can reap the benefits of digital twins without incurring the high learning curve that comes with custom, more complex systems by utilising off-the-shelf solutions. As companies gain experience and proficiency with these technologies, they can eventually upgrade to more advanced systems that better suit their unique requirements and long-term objectives.
A phased approach is advised for companies wishing to implement Digital Twin technology. Organisations should first implement a simple model that takes care of their pressing issues. Starting with a low-latency data integration strategy, for example, can set the stage for more sophisticated functionalities. Modularity should be considered in the design of this initial model, which could be considered an Archetype 1 (AT 1) twin to facilitate future improvements. New capabilities and technologies can be gradually added to the organisation in accordance with a clearly defined roadmap as its needs change. By taking this method, the risk is reduced, and the DT is guaranteed to change along with the organization's goals as it grows.
The research's conclusions highlight the necessity for a stronger empirical basis in order to comprehend the obstacles and difficulties related to DT adoption in the circular built environment. Future studies should use workshops that bring together practitioners and experts from different fields, as well as a larger pool of interviewees. An enlarged approach of this kind would offer a more thorough comprehension of the problems involved, possibly exposing trends and insights that the current study did not identify. A more nuanced set of recommendations that better reflect the realities of DT adoption may result from the diversity of viewpoints.

The study emphasizes that efforts to classify competencies and company profiles did not produce discernible trends, highlighting the inherent messiness of practice in the circular-built environment. The absence of a well-defined classification implies that the integration of Digital Twin technologies cannot be easily categorised. Instead of trying to fit this complexity into predetermined frameworks, practitioners and researchers should embrace it. It is recommended that future research investigate alternative approaches to categorisation or adopt more flexible approaches that can account for the various realities of actual DT adoption.

This chapter's recommendations offer a strategic road map for removing obstacles and difficulties related to implementing Digital Twin technologies in the Dutch circular-built environment. Organisations can better navigate the complexities of DT adoption and use these technologies to advance their circularity goals by promoting collaboration, facilitating easy entry, adopting a phased approach, gathering more empirical evidence, and acknowledging the complexity of practice. These recommendations not only address the immediate challenges faced by early adopters but also provide a foundation for sustained innovation and growth in this emerging field.

7.0 Reflection

The approach used in conducting this research was partially successful. The circularity matrix as a tool for categorizing organizations was potentially lacking in scale and was based on a theoretical view of the built environment. Meaning each of the organisations either defied expectations or fir into multiple parts of the matrix. Furthermore, their position in the matrix could also vary from project to project or could also result from the changes that organizations undergo naturally as time passes. The archetypes constructed were based on generic descriptions of digital twin archetypes and from this the supporting networks of technologies was constructed. This was also done to clarify the type of archetype that was used or preferred by interviewees. This model was also perhaps lacking as several of the interviewees stated that they used or preferred an archetype but that some modifications were still needed. These two components of the methodology both still were essential components of the thesis, but they did require considering them differently than initially expected. The matrix as a tool for creating a common taxonomy was essential as it created a reference point for comparing different organizations. With larger data sets patterns might become clearer but for this thesis its function as a medium for comparison made the formulation of an answer to the research question possible. Furthermore, the use of qualitative research methods to answer the research question appears to have been the correct choice as the open ended nature of this type of research, that analysis the needs, wants and perceived barriers and challenges, necessitates qualitative interviews with persons that represent to the best of their capacity their affiliated organizations. The method of using a somewhat combined interview and case study methodology was necessary, however the benefits of conducting it in a more interviews would have been beneficial but would have lacked the granularity that more extensive interviews granted.

The benefits of this thesis are the added value as an overview of the potential actual challenges that organisations will encounter trying to adopt digital twins for various circular purposes. Additionally, there is a clearly available comparison between the barriers that potential adopters will perceive and the solutions already available, making adoption of digital twins possibly more likely, thus furthering the adoption of digital twins. Furthermore, this thesis takes barriers and challenges from generic to specific by defining categories through the combination of generic domains and experienced or perceived obstacles from the perspective of industry experts. Additionally, the archetypes created provide a new and circularity specific way to categorize digital twins.

The choice for mentors was specific to Paul Chan and Vincent Gruis. The feedback they gave often was succent and coherent but also came from two different perspective. Vincent Gruis is an expert in the field of circularity and Paul Chan is a researcher that brings a degree of philosophical thinking and dept to his critiques. Not all feedback was always agreed with, but it always sparked a new round of re-examining the additions and iteration when writing the thesis. Their patience and willingness to repeat feedback created a process wherein this research could be conducted through writer's block and personal health issues. The feedback if not agreed with was always heeded and thoroughly noted downs as to be considered fully after the meeting.

The process of writing a thesis was a difficult one as after setbacks in the initial stage morale took a bit of a dive. Despite this the work continued and volume increased as the concept of working through the pain was applied. This created a scenario were putting your head down and pushing through became the norm. At a certain point this was no longer possible as writing a thesis requires you to look up and consider the entirety of the report. However, at this point it was difficult to find the forest through the trees. After leaving it for two weeks and restarting a fresh perspective created room for analytical thinking to once again become part of the process. Not giving up is necessary, but putting your head down and working Is not the way to conduct research as it can lead to a loss of perspective. Additionally, literature not based on practice and the specific context in which the study takes place does not survive contact with reality. This however is not a negative as the differences themselves allow for research to add to the collective.

The master track MBE was focused on providing advanced knowledge regarding management in the built environment with a key focus on integrating sustainability throughout decision making processes. Digital Twins in the circular Built environment are tools to help make decisions, additionally the structure of this thesis creates a starting point for decision making regarding the integration of these technologies by indexing potential obstacles to the implementation of a tool that could enable the circular built environment. This research was created to collect and index various interviewees with different perspectives and needs.

The recommendations were informed by experts that are active in the field that have experience with the circular built environment in a variety of ways. The research started of considering both archetypes and the matrix as tools for categorizing reality, however reality is not neat and not flued. This made the matrix, for example more of a tool for fostering a common taxonomy as mentioned earlier and made clear that the archetypes are more modular than anticipated. These realizations created necessity for more in depth analysis and considerations considering the complexity of reality. This thesis could be considered a starting point. All components, the archetypes and matrix, could be considered as use fool tools for conducting further research. Additionally, barriers and challenges could also be used as a starting point in other research and is definitely not definitive and can be added to during further research.

Ethical consideration of this thesis stem from three points of concern. The first is the perspective of the interviewees, the content of the thesis and wider societal impact. The interviewees are anonymized to protect their privacy in accordance with the standards set by the technical university delft. If interviewees made statements regarding certain subjects or proprietary tech and wished these to be omitted this was adhered to. Also, the perspective of the interviewees and their own knowledge base also considered, that's why their positions in their perspective companies were also taken into account. The content of the thesis dealt with barriers and challenges and in these ethical concerns regarding data privacy, security and ownership for example were also addressed. It should be noted that equity and access are an ethical consideration as well. For wider societal adoption of these crucial technologies a lot of financial, technical and other resources will be needed. This could provide well-resourced organisations and advantage when competing in the circular built environment, this is something that should be taken into account and perhaps considered during further research.

In this thesis, the concepts of Digital Twins and circularity are examined in tandem to explore their interdependent relationship within the Dutch circular-built environment. Digital Twins—virtual replicas of physical assets or systems—hold significant potential to enhance sustainability efforts by enabling better resource management, performance monitoring, and lifecycle assessments. In a circular economy, where materials are reused, refurbished, or recycled to reduce waste, Digital Twins can play a transformative role by providing real-time data and insights that facilitate closed-loop processes. This analysis delves into various factors—such as data standardization, regulatory frameworks, financial constraints, cultural hesitancy, and technological readiness—that impact the integration of Digital Twins within circularity-focused projects. By understanding these barriers and challenges, the thesis aims to provide insights into how Digital Twins can effectively support circular economy principles, outlining the adjustments needed to strengthen the synergy between these two forward-looking paradigms. This thesis is not only the culmination of an academic journey, but also the fulfilment of a personal ambition. During my youth I was always fascinated with the application of technology to various factettes of life. In Suriname these applications were sparce but were thanks to factors such as the internet still something I could immerse myself in. This fascination was fostered by my family whose values in fostering curiosity and academic achievement lead me to want to gain not only knowledge but help create it by diving into topics, discovering connection or just by discussing topics and intersections. The curiosity with technology at a young age was also fostered by individuals around me that were also involved with research and technology, this is where I first learned about digital twins. I was thoroughly fascinated with the idea of digital representations of reality and its applications. Whenever the opportunity presented itself to choose a topic for assignments, I would try to incorporate technology or digital twins in to the subject. When the time came to make my decision regarding my university track, I chose the one Architecture as creation of the spaces we lived in fascinated me, I enjoyed employing creativity to create something that would fulfil a need and solve a problem. This evolved into how the space is created, what are the problems that arise during this complex process and how are these solved. When trying to create circular built environment digital twins were named as a way to facilitate various aspects. This created the opportunity to finish my master track by writing a thesis that would add to the pool of knowledge regarding a topic that initially more than a decade ago sparked my curiosity, and that potentially further the integration of technology into the built environment by facilitating a transition (towards circularity) that is becoming more and more crucial.

Appendix - Interview Protocol

- Eigen intro en in stemming eigen intro interviewee

Step 1: Interviewee Data

- What is your name?
- Which company or organisation are you currently employed at?
- What is your Current Job Title?
- What does your job entail?

*Introduction

Step 2: Company/Organizations description

- What activities in the built environment does your company/organisation undertake in general?
- Where is your company/organisation based?
- What is the size is your company/organisation?
- What is the companies/organisations financial turnover?

Step 3: Position in the CBE (based on circularity activities and strategies provided)

- What circularity-oriented activities does your company/organization undertake?
- Given the stages of a building's life cycle and corresponding circularity strategies where does your company/organization execute the stated activities?

- Please use the Matrix provided to answer the question –

(*) bases on an online description of your company/organization you also [-], could you tell me more about that?

(*) and where would you place it in the Matrix?

Step 4: Does your company/organization use Digital Twins to support the circularity strategies you employ?

Step 5 (a): Interviewee Definition of Digital Twins (Information on Digital Twin Architypes provided)

- Which of the digital twin archetypes provided best fits the circularity strategies your companies/organization employs?
- * why

- Please place the digital twin archetypes in the circularity matrix.

Step 5 (b): Interviewee Definition of Digital Twins (Information on Digital Twin Architypes provided)

- Which of the digital twin archetype description best fits the Digital Twin or Twins your company/organization employs?
- How do they support the circularity strategies your companies/organization employs?
- Has it been beneficial to your company/organization?
- Please place the digital twin archetypes in the circularity matrix.

Step 6 (a): Barriers to Digital Twin implementation for circularity

- For the Circularity strategies employed by your company/organization and the corresponding Digital Twins what are the perceived barriers to implementing Digital Twins?

Step 6 (b): Challenges to Digital Twin implementation for circularity

- What were the challenges experienced during the implementation of Digital Twins for circularity purposes?

Step 7: Cross reference Barriers and Challenges with circularity Challenges (based on own list)

- You mentioned the following barriers/challenges [-], could you elaborate upon whether these are related to circularity or the implementation of Digital Twins?

Step 8: Ending Interview

- Was there anything I failed to mention?
- Is there anything you would like to mention about the use of Digital Twins to support circularity strategies and the accompanying barriers or challenges?

I would like to extend my sincere gratitude for taking the time to participate in this interview. Your valuable input has contributed significantly to this research efforts and your responses have provided invaluable information.

If there are any additional thoughts or reflections you would like to share after the interview, please feel free to reach out. And if you are interested in the completed study, I would be happy to share it with you.

Once again, thank you for your time, cooperation, and valuable contributions to this thesis. I truly appreciate your willingness to share your expertise and experiences.

Appendix – Occurrence barriers and challenges

	Interviewees	combining Data (DWSS)	Data Ownership	Data Privacy	Data Safety	Diversity within sources	Financial Capacity	Lack of Clear Buisness Models	Lack of Parties Capable of Making DT's	Regulatory challenges	Standerdisation of data	Technological Hesitancy (cultural)
DT used	intv. 1	0	1	0	0	0	1	0	0	1	1	1
	intv. 2	1	0	0	0	0	1	1	0	0	1	0
	intv. 3	0	0	0	0	0	1	0	0	1	1	1
	intv. 6	0	1	0	1	0	1	1	0	0	1	0
	intv. 8	1	0	0	0	0	0	1	0	0	1	1
	intv. 9	0	1	0	0	0	1	0	0	0	0	1
	intv. 11	1	0	0	0	0	0	1	0	1	1	0
	intv. 13	0	0	1	0	0	1	1	0	1	0	1
	Total Occ. Challenges	3	3	1	1	0	6	5	0	4	6	5
		38%	38%	13%	13%	0%	75%	63%	0%	50%	75%	63%
DT not used	intv. 4	0	0	0	0	0	1	0	0	1	1	1
	intv. 5	0	0	0	0	0	1	0	0	0	1	1
	intv. 7	0	0	0	0	0	0	0	0	0	1	1
	intv. 10	0	1	0	0	0	0	1	0	1	0	0
	intv. 12	0	1	0	0	0	1	1	0	1	0	1
	Total Occ. Barriers	0	2	0	0	0	3	2	0	3	3	4
		0%	40%	0%	0%	0%	60%	40%	0%	60%	60%	80%

Appendix – Circularity Strategies

(Based on Bocken et al, 2020)

S= Slow	P= Pre-Build
N=Narrow	C = Construction
R= regenerate	U =Use
C= Close	E =End of Life

S-P: S1, S2, S3, S4, S5, S6, S10, S12

1. Design for physical durability Design products that degrade more slowly than comparable products on the market.

2. Design for emotional durability Design products that users will love and trust over a long period of time. This could be done through long term warranty for materials

3. Design for ease of maintenance and repair Design products that can be easily maintained or repaired. Maintaining means inspecting the product to retain its functional capabilities. Repairing is about restoring a product to a sound/good condition after decay or damage.

4. Design for easy dis – and reassembly Design products that can be easily separated and reassembled.

5. Design for upgradability A product is upgradable if its functionality or performance can be improved during or after use.

6. Design for standardization and compatibility Create products, components or interfaces that also fit other products, components or interfaces.

10. Provide an unconditional lifetime warranty Offer your customers a life-time warranty, adding a promise to products that are made to last.

12. Provide the product as a service Offering the product as a service keeps the ownership with the firm and creates incentives to increase their lifetimes. You can Offer product-, use-, or results-oriented models.

S-C: S11, S12

1. Encourage efficiency Encourage your customers to moderate the consumption of your products. This by encouraging users to maintain and trade back products once they don't use it anymore.
2. Provide the product as a service Offering the product as a service keeps the ownership with the firm and creates incentives to increase their lifetimes. You can Offer product-, use-, or results-oriented models.

S-U: S7, S13, S14

7. Enable users to maintain and repair their products Create services that enable users to care for their product. Through providing access to repair knowledge and an inventory of spare parts.

13. Organize maintenance and repair services Make sure that your products can last longer through maintenance and repair services. They can be offered by the manufacturer of a product or by third-party providers

14. Upgrade and adapt existing products A product is upgradable if its functionality or performance can be improved during or after use. Try and integrate upgrading services into your offering.

S-E: S8, S9, S15

8. Remanufacture existing products and components Recover value from collected end-of-use products by reusing their components for the manufacturing of products with the same functionality. For example, through collecting and remanufacturing them into as-new certified spare parts.
9. Repurpose existing products and components Take existing products and components and take them out of their context to create new value with them. For example, by adding additional use cases to building components.

15. Turn disposables into a reusable service Make use of or provide services that replace disposable with durable products. These disposable parts can be reused by including actors retail brands, service providers (e.g., cleaning and transport service) and end users.

N-P: N1, N2, N3, N5

1. Design with low-impact inputs Design products with 'ingredients and materials that require less land, energy, water and/or materials to produce.
2. Design light-weight products Design products that are lighter than comparable products on the market to reduce energy to transport.
3. Design for multiple functions Design products with multiple functions. Multi-functional products can reduce the overall number of products and may be usable by different user groups.
5. Enable and incentivize users to consume less Incentivize users to use less energy or material during the use of energy or material-using. The firm HOMIE offers washing machines through a pay-per-wash model. By monitoring user behaviour, the company increases the resource efficiency.

N-C: N6, N7

6. Organize light-weight urban transport Organize lighter forms of transportation. The lighter the vehicles, the lower the amount of energy and materials required to transport people and goods.
7. Localize supply where appropriate Find more local suppliers, where appropriate. More local suppliers decrease the amount of energy needed to transport goods.

N-U: N8

8. Maximize capacity use of products Maximize the degree to which the capacity of a product is used. This is sometimes referred to as 'sharing', where multiple user groups have access to the same product.

N-E: N4

4. Eliminate production waste Eliminate any type of waste from production processes, for example material scraps or excess heat and electricity. For example, waste and save cost reduction through centralized disposal, Artificial intelligence enabled image recognition software and training based on gathered waste data.

C-P: C1, C2, C3, C4

1. Design with recycled inputs Design with materials that have been recycled from other products and components. The 'Design for Recycled Content Guide' supports firms in opting for more recycled content in their products.

2. Design components, where appropriate, with one material Composite materials are often hard to recycle because they cannot be separated. Design components, therefore, where appropriate, with only one material to increase recyclability.
3. Design with materials suitable for primary recycling Try and design for primary recycling, that is: recycling that can turn materials into materials with equivalent properties.
4. Design for easy disassembly at the end of the product lives Easy disassembly allows product components to be more easily recycled.

C-C: C8, C9

8. Build local waste-to-product loops Create local resource loops by turning the waste of a given facility into new products that can be sold back to the facility. For examples allow for local collection of components or raw materials and provide these to local projects from the same owners or other initiatives
9. Engage in industrial symbiosis Share or exchange by-products, materials, energy, or waste among nearby firms. For example, using by products from other nearby industries, or providing wate material after use to other industries.

C-U:

C-E: C5, C6, C7, C8, C9

5. Reuse and sell components and materials from discarded products Create new value from wasted products and components.
6. Enable and incentivize product returns Make sure that you can get the products back that you put on the market for example allow owners to scan a QR code or other tracking technology in to facilitate sending back to manufacturers Sending back products earns users credit for their next purchase.
7. Recycle products in proper facilities Make sure that the products you put on the market get recycled in proper facilities. The initiative 'Closing the Loop' supports users and sellers to be material-neutral and waste free. This by facilitating the gathering of materials and components and properly recycling them.
8. Build local waste-to-product loops Create local resource loops by turning the waste of a given facility into new products that can be sold back to the facility. For examples allow for local collection of components or raw materials and provide these to local projects from the same owners or other initiatives
9. Engage in industrial symbiosis Share or exchange by-products, materials, energy, or waste among nearby firms. For example, using by products from other nearby industries, or providing wate material after use to other industries.

R-P: R1, R2, R3, R4, R8, R10

1. Design with renewable materials Design products with renewable and low-carbon materials. Timber wood, for example, can replace non-renewable building materials. Renewable materials should only be chosen when its extraction rate is equal to or lower than its recovery rate. Further, next to its properties, materials need to be selected based on their expected end-of-life treatment to avoid unintended consequences.
2. Design self-charging products Design products that can charge themselves with renewable energy. This for example through integration of solar cells in different components.
3. Design with living materials Living materials leverages the properties of natural materials. Evocative, for example, produces mycelium-based fibres and materials with natural glue properties.
4. Design with non-toxic materials Avoid using toxic materials and substances in any of your products or operations. Toxic substances tend to accumulate in the biosphere and cause negative health effects for humans and other species.
8. Embed renewable energy production in the existing infrastructure Find ways of making renewable energy production part of the existing infrastructure. 'Solar Roadways' has developed a modular system of solar panels that can be walked and driven upon.
10. Manage and sustain critical ecosystem services Engage in projects that manage and sustain the natural ecosystems that surround and/or affect your business operations

R-C: R5, R6, R7, R9, R10

5. Produce and process with renewable energy Build up your capacity as a company to produce and process with renewable energy.
6. Power transportation with renewable energy Find ways to power your transportation needs for materials for example with renewable energy. Through a light-weight mobility system, powered by renewable energy.
7. Power the use of the product with renewable energy Find ways of powering your product with renewable energy, through creative partnerships or product and service design. Through providing portable devices with photovoltaic panels that can power every-day electronics.
9. polluted ecosystems Contribute to regenerating polluted ecosystems that affect your business. The Ocean Cleanup Project develops technology for collecting environmental waste.
10. Manage and sustain critical ecosystem services Engage in projects that manage and sustain the natural ecosystems that surround and/or affect your business operations

R-U: R10

10. Manage and sustain critical ecosystem services Engage in projects that manage and sustain the natural ecosystems that surround and/or affect your business operations

R-E: R9, R10

9. polluted ecosystems Contribute to regenerating polluted ecosystems that affect your business. The Ocean Cleanup Project develops technology for collecting environmental waste.
10. Engage in projects that manage and sustain the natural ecosystems that surround and/or affect your business operations

Appendix – Circularity Barriers

Barrier Type	Barriers
Cultural	- Hesitant company culture and change resistance - Lack of interest in recycled and remanufactured products - Reluctance and risk aversion of construction stakeholders
	- Perceived poor quality of refurbished and recycled products - Preferences of virgin construction materials over reused and recycled products
	- Absence of CE and sustainable cultural behavior
Market	- Lack of market pressure and competition - Uncertain market demand for refurbished, remanufactured, and recycled products
	- Immaturity of market and relevant technologies - Limited availability of recycled materials and reused products
	- Lack of market mechanisms for waste recovery - Poor demand for environmentally superior technologies
Knowledge	- Lack of CE knowledge, technical capabilities, and expertise in construction - Limited stakeholder awareness of circular materials, products, services, and strategies
	- Limited CE awareness across the construction supply chain network - Lack of appropriate CE training, development programs, and technical support
	- Lack of data and information on circular construction materials, products, and services - Insufficient understanding of the benefits of circular materials and products
Financial	- Higher upfront investment costs - Lack of funding for circular business models - Lack of capital financial resources
	- Lack of economic benefits in the short run - Low prices of virgin materials - Unpredictable financial returns and economic savings
	- High cost of eco-friendly materials and products - Unclear financial business case for CE construction
Management	- Lack of top management commitment, support, and leadership - Lack of standard indicators, systems, and data collection for performance assessment - Limited circular designs in construction projects - Lack of successful business models and frameworks to implement circular construction projects - Complex planning requirements and management processes - Lack of design tools and strategies for circular business models and circular products
Regulatory	- Lack of a regulatory framework and appropriate policies for CE construction - Lack of government financial support mechanisms and tax incentives - Lack of regulatory pressure and stringent regulations - Lack of clearly defined national goals, targets, and visions for CE construction - Lack of sound infrastructure for CE construction - Poor institutional support framework for CE construction - Weak enforcement of rules and regulations for environmental protection - Lack of incentives for designing end-of-life products
Technological	- Lack of technology infrastructure readiness - Lack of proven technologies and equipment for CE construction - Lack of robust information systems to track recycled materials - Lack of technological eco-innovation capacity - Lack of enabling digital technologies and solutions - Limited technology design for end-of-life products
Supply Chain	- Fragmentation and complexity of the CE supply chain network in construction - Lack of cohesive reverse logistics network and facilities - Lack of appropriate supply chain partners - Lack of integration and collaboration among supply chain partners in construction - Limited circular procurement practices and strategies in construction - Insufficient suppliers of circular materials, products, and services
Stakeholder	- Poor cooperation, collaboration, and communication among stakeholders in the CE value chain - Lack of data transparency and information sharing - Lack of appropriate partners and participative network - Lack of trust among stakeholders - Lack of support and involvement of stakeholders
Technical	- Lack of technical and technological know-how to implement CE practices - Technical complexity in transitioning from linear to CE construction projects

	- Scaling difficulties in CE construction - Insufficient technical resources and infrastructure (collection centres, recycling plants) for CE construction - Complexity of construction products and projects
Organizational	- Increased organizational processes and planning burden - Unsupportive business culture and organizational norms - Excessive dominance of traditional resource -intensive business models in construction - Inadequate organizational resources and capabilities - Complex administrative requirements and legal procedures - Lack of strategic organizational planning practices for CE

Appendix Table 1: Barrier Types and sub-types adopted from Wuni, 2022.

Broad categories	Barrier
Economic/Financial Barrier	High cost of reclaimed materials Low market value Low landfill cost Limited market supply and demand Design cost Budget and upfront cost Duration and labour cost Cost of approach Market of recovered materials Access to finance Material cost Difficulty to break into the established markets dominated by industrial materials Market and business prefer advantage demolition rather than deconstruction Low cost of CDW disposal Low cost of virgin materials relative to secondary ones Lack of competition Client readiness to pay for extra Less manpower and more mechanization Estimation challenge Insurance cost Additional construction cost for reclaimed and recycle materials Lack of incentives and defined benefits Immature recycling market operation Profit seeking first
Technical Barriers	Design codes focusing on reclaimed materials is limited Lack of building design standards for reducing CDW Lack of policy incentives Lack of regulations and implementation guidelines Prohibitive domestic policy Lack of green designing of construction projects Lack of storage facility for reclaimed materials and access to the site Poor skills of operatives related to construction waste reduction and treatment Prohibitive international policy Lack of information about existing structure and materials Lack of design standards in existing regulations Lack of equilibrium in recycling and reuse marker Lack of data related to CDW generation for policy decision making Lack of guidance for effective CDW collection and sorting Inadequate policies and legal frameworks to manage CDW as well as lack of supervision on CDW management Improper urban planning Inherent complexity of transforming to circular economy in CDW management Lack of mature and complete municipal regulation system to guide CDW Lack of government support Lack of CE marking strategies
Social Barriers Cultural Barriers	Lack of awareness, knowledge and understanding on environmental impact of polluted waste and pollution of virgin feedstock Lack of demand in composite construction Lack of education on CE strategies among stakeholders Society evolution Lack of client demand Market preparedness Construction sector inertia Low image placed on individuals who use reclaimed and recycled materials Unrealistic hypothesis Aesthetic trend Strong belief that waste management is more expensive

	Lack of concern for reclaimed materials Lack of trust and acceptance of reclaimed materials Lack of trust in data Consumer society: consumer culture and perceptions for reclaimed materials Perception of second-hand materials being sub-standard Lack of global vision Lack of collaboration and value chain thinking Cultural beliefs Hesitance to CE integration and business models Resistance to change of old generation Lack of empirical based literature on the barriers Preference for off-site CDW sorting/landfilling over on-site sorting due to lack of incentives User preference for new construction materials over reused/recycled ones Ingrained linear mindset Culture of waste behavior-assumption that waste is inevitable
Technological Barriers	Lack of performance guarantees for reused materials Lack of own technology to recover and reuse materials by managers Lack of producer-based responsibility system in production of construction materials Insufficient application of the 3R approach by construction practitioners and projects Immature recycling technology
Environmental Barriers	Lack of environmental protection in construction waste management Lack of incentives on environmental assessment methods Environmental impact: emission from transport, use of virgin feedstock

Appendix Table 2: Barrier Types and sub-types adopted from Osei-Tutu et al. 2022).

Broad categories	Barriers
Economic	Lack of business grants Under-developed/lack of market mechanisms for recovery/reuse of materials High costs of deconstruction, separating, treating, transportation, and storage of CDW High prices of recycled/reused materials/products Lack of reward and penalty schemes for CDW management operations Product prices do not take environmental costs into account Lack of financial aid Culture of rapid returns on investment and high prices for green buildings Cost of developing products certifications High investment costs of waste technologies
Informational	Lack of research, education, and information Social and behavioural aspects of modern consumerism Lack of publicity and information campaigns Limited environmental management programs and facilities at academic institutions
Institutional	Lack of strategic vision and collaborative platforms Lack of thinking about buying a service instead of having the ownership Lack of information about DFD, green design, and end-of-life products Lack of knowledge about circular tools (EPDs, Material Passports, certifications, etc.) Insufficient application of waste hierarchy (overemphasizing recycling) Lack of guidance and tools for the implementation/assessment of circular buildings

Political	Lack of regulatory instruments Lack of flexibility in the building codes and regulations Lack of EPD international standardization Lack of producer-based responsibility system and regulatory frame for integrated resource management Lack of a waste code to guide CDWM and discourage landfilling Lack of tax actions Lack of laws to assign a minimum percentage of CDW for reusing and recycling Lack of land-use zoning and rational urban planning Lack of circular vision Lack of support for research, innovation, information, and business procurement strategies Lack of effective supervision from the government (qualified professionals and budget)
Technological	Lack of integrated CDW processes, tools, and practices Recycling practices are thwarted by limited separation of materials, logistical barriers, and lack of process to produce easily disassembled products Lack of tools for identifying, classifying, and certification of salvaged materials Lack of standardized spatial geometries and limited visualization for DfD Lack of an information management system Lack of quality and availability of data (privacy, trust, ownership, access) Difficulties in understanding and developing EPDs Lack of documentation of new and used building products Lack of datasets and tools compliant with BIM

Appendix Table 3: Barrier Types and sub-types adopted from Munaro and Tavares (2023)

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