Circular Industrialised Construction

Strategies for the operations and end-of-life phases

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by

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Preface

This thesis researches the strategies applied by construction companies that are constructing Circular buildings through Industrialised Construction. This research is executed as part of the graduation process for the master Architecture, Urbanism and Building Sciences. In specific the track Management in the Built Environment. This thesis research is executed at the Faculty of Architecture and the Built Environment at Delft University of Technology.
Therefore, with the document in front of you, my study journey at the Faculty of Architecture and the Built Environment concludes. As I am writing this, I am faced with some mixed feelings. On the one hand, I am relieved that the process of this thesis and graduation is near completion. On the other hand, it also saddens me as I realise the end of my time at Delft University of Technology and in specifically the Architecture faculty is upon me. During my time at the university, I was faced with many challenges, both in academic and personal matters, that tested my abilities and resilience.
I want to mention a specific moment in my time at Delft University of Technology that has and will continue to impact my life in its entirety. In the first two weeks after the start of the bachelor of Architecture, my father became terminally ill. Not long into my first year at Delft University of Technology, he passed away. This tragic moment will stay with me my entire life and I will always associate it with this University. Especially, how welcoming the community was and remains. And most importantly how I have sensed a kind of belonging in my time here. I will look back on that and will continue to treasure that for as long as I possibly can.
Knowing this means only one thing. I am immensely proud of the work I have produced. If this in one way or another contributes to the built environment I am very happy. The process of completing this thesis has once again shown me for sure that the faculty of Architecture and the construction industry is the right fit for me.
The past year has been a roller-coaster of experiences. With some significant moments that alleviated the experience of this thesis. However, there were also definitely some experiences that were not a highlight during the process of creating this master thesis.
I want to dedicate this space to thank a few persons within the faculty for their efforts and contributions to my thesis research. First, both my supervisors, Daniel (M.) Hall and Angela Greco. I always looked forward to meeting with either of you or both of you. Your expertise on the topics of the built Environment resulted in valuable contributions to this research. My meetings with both of you were a highlight of this thesis research as it made me realise I am not doing this all by myself. Besides my supervisors, I want to thank Paul Chan for his efforts at the very beginning of this thesis research and for giving me the freedom and guidance in finding my thesis research. Without those brief discussions, I would not have made it. Thank You!
I want to thank all the participants and the case companies involved for their contributions to this research. My conversations and discussions with all of you were a highlight of the entire process and I've tried my best to make sure all your knowledge & experience can be used for future research. This is also the place where I would like to thank and express my gratitude to my friends and family who have supported me through their love motivation and encouragement.

I did it!

Dennis Lagendijk
Delft, April 2024

Abstract

Industrialised Construction gains traction as it is seen as a solution to create resource efficiencies in the Built Environment. In practice, this increase in industrialisation leads to an increase in standardisation efforts. Meanwhile, the Circular Economy is incrementally being introduced to the Built Environment. Circular Building is often applied through designing or constructing buildings made out of modular components. The combined efforts of Industrialised Construction and Circular Building, often depicted as standardised modular building or Circular Industrialised Construction, are being researched. However, we know very little about the operation and end-of-life strategies of these buildings.

This research examines the strategies three case companies apply for their standardised modular buildings' operation and end-of-life phases. The research is carried out by conducting interviews with employees of the three case companies. The initial selection of case companies, CitizenM, Daiwa Modular Europe, and Home.Earth, is based on their utilisation of industrialised building methods and their assertions regarding circularity. Additionally, the companies are selected by a few diversifying characteristics, such as whether they are owner/developer, the type of real estate they develop, and the type of components they manufacture (volumetric or planar). After the initial within-case analysis, a cross-case analysis is carried out.

The case studies demonstrate that there exist many differentiating approaches to the operation and end-of-life phases of Circular Industrialised Construction buildings. A reason for these varying methods is on which building layers significant efforts are made to circularise the buildings. An important enabler of circularising the operation and end-of-life phase is to appropriate the design phase and extensively collaborate in or with the manufacturing phase. Additionally, some pitfalls are identified for the application of Circular Industrialised Construction.

Based on the initial results, a Circular Industrialised Construction framework is being proposed. The framework combines the different Shearing Layers Concept and the different phases associated with Industrialised Construction and design. The framework categorises the identified strategies in the different phases based on the Shearing Layer Concept. The aim is to provide a directory that allows companies to incrementally implement circularity efforts or adopt an Industrialised Construction approach.

Contents

1 Context

1.1. Background Information

For a long time, the impact of the construction sector on co^2-emissions has made headlines ("Hout moet oplossing bieden voor verduurzaming woningbouw", 2021). In efforts to reduce the sector's impact, several studies have been conducted to understand where the environmental impact of the construction sector originates from. One of the identified contributors is the linear usage of construction materials in buildings. Materials are produced to be installed in a building and after their lifetime are demolished and moved towards a landfill. In the production of these materials, a large part of the co^2-emissions are polluted. To prevent these emissions from going to waste the reuse ability of these materials is increasingly considered. Here the notion of the Circular Economy envisioned by the Ellen MacArthur Foundation is often implemented in the construction sector. The Netherlands has even announced the ambition to have a circular economy by 2050.

The ambition of the Netherlands to transition towards a circular economy has made the construction sector aware of its impact on the environment. To successfully transition towards a circular economy the butterfly diagram by the Ellen MacArthur Foundation has been introduced and applied in the Built Environment. The diagram presents two loops, which serve as pillars of a circular construction sector (figure 1.1) (The Ellen MacArthur Foundation, 2023). The right loop(in blue) represents the technical loop, and the left loop(in green) represents the biological. Efficient solutions for the construction sector need to be able to include both the technical and biological loops (Stahel, 2013). An example of the application of these loops is the use of reversible connecting details when working with wooden prefab elements (Akinade et al., 2020). The biological loop is accounted for with the wooden materials. At the end-of-life of the wooden material, it can be reintegrated into the biological loop. The technical loop is accounted for by utilising reversible connecting details, so the material can be disassembled.

A second contributor to the construction sector's co^2-emissions is resource inefficiency during the construction process. Recent studies have estimated that about 10% to 25% of materials procured for the construction of a building end up as waste in landfills (Ajayi et al., 2017). About 11% of the total co^2-emissions in the Netherlands can be attributed towards construction materials and the construction process. This means that in the Netherlands 1.1% up to 2.75% of co^2-emissions are emitted to then be transformed into waste in landfills.

Research into efforts to combat waste production during the construction process has been reviewed from many different perspectives. One of those solutions is the industrialisation of the construction sector; Otherwise known as Industrialised Construction. The terminology has long been around in the construction sector. However, recently it has been gaining traction as a solution to the resource inefficiencies that occur in the construction sector. The definition of Industrialised Construction has long been debated, for this research, it is considered a more holistic terminology that aims to improve efficiency and reduce defects in the construction process.

In practice the application of Industrialised Construction can be categorised into a few groups. For instance, the application of innovative tech-

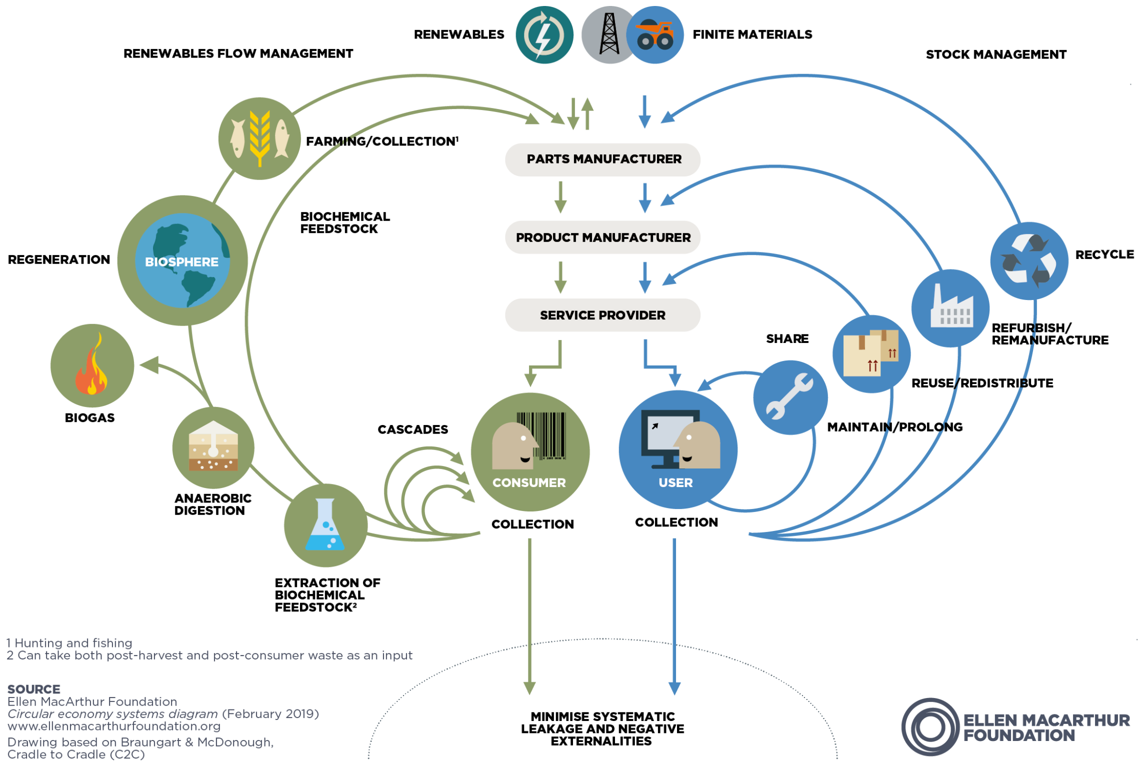


Figure 1.1: The butterfly diagram developed by the Ellen MacArthur Foundation (The Ellen MacArthur Foundation, 2023)

nologies on the construction site, such as robotics. Another example is extensive prefabrication on an off-site facility. Where the off-site facility is often organised through an assembly line. In this research only the application of Industrialised Construction through an off-site facility that manufactures buildings utilising an assembly line is considered.

The combination of the concepts of Circular Building and Industrialised Construction has coined the term Circular Industrialised Construction. This encapsulates the process of constructing circular buildings that are manufactured utilising Industrialised Construction methods. These buildings often consist of large similar units. Due to the needed recurrence, an assembly line manufacturing process creates efficiencies in the employment of resources.

1.2. Problem Statement

Recently there has been a rise in the application of Industrialised Construction in the Netherlands. More companies are implementing this method since it allows for more efficiency in material usage, labour usage, construction time and overall improvements in quality assurance. The theory behind Industrialised Construction implies that companies can improve the design and construction through extensive collaboration with partners in the building process. This is based on the assumption that due to repetition, building elements are upgraded to support a more streamlined manufacturing and construction process.

The impact of the construction sector & built environment on co^2-emissions has been extensively researched. To reduce the environmental impact of the construction sector and the built environment the circular economy has been gaining traction. Furthermore, the circular buildings that are built consist mostly of lighthouse projects. Research into the application of circular building consisted mostly of reusing existing buildings as material banks for upcoming projects. One of the lessons learned in the application of circular buildings is the extensive preparation needed in the front-end phase of these buildings.

Both subjects, Industrialised Construction and circular building, require more preparation in the front end of projects than traditional non-circular buildings. In this phase, both subjects supplement each other. Several applications of circular building and Industrialised Construction are being tested and implemented. Nevertheless, our understanding remains quite limited regarding strategies in place for the operation and end-of-life phase of circular buildings that are constructed through Industrialised Construction methods.

However, there is little research on operation and end-of-life phase strategies for circular buildings that are constructed through Industrialised Construction. Since the entire concept of circularity is based on its ability to reuse components, the strategies in place to ensure re-usability are engaging subject matters. Existing strategies related to the operation and end-of-life phase are usually related to buildings that are not designed and built circularly. This means that companies designing, building, assembling, operating and dismantling these circular buildings face new challenges that they need to overcome. Reviewing these challenges and understanding the strategies that these companies have developed to mitigate these challenges is unexplored research.

1.3. Research Objectives and Research Questions

This research aims to understand the challenges that exist for Circular Buildings that are constructed through Industrialised Construction. Reviewing the strategies put in place by these companies to mitigate these challenges is an important aspect of this research. To review these mitigating strategies several aspects that are already identified as existing barriers to the application of circular building will resurface. Examples of those barriers are, building codes, conservative attitudes in the construction sector, and design challenges. The compelling part of this research will be reviewing how the barriers are diminished by the researched companies.

This research seeks to gain insights into the industry-wide application of strategies for the operation and end-of-life phases of buildings. This research reviews how companies participating in Industrialised Construction and Circular Building formulate strategies for the operation and end-of-life phases of buildings. To retrieve these insights the following main research question is formulated:

"How can strategies for circular buildings using industrialized construction methods account for the operational and end-of-life phases?"

To answer the main research question, several sub-research questions have been developed. The sub-research questions are:

1. *What strategies for Circular Building using Industrialised Construction methods can be identified?*
2. *How are the operation and End-of-Life phases taken into consideration during the strategy-making process?*
3. *What are the pitfalls in the strategy-making process for the operation and End-of-Life phase of circular buildings using industrialised construction methods?*

1.4. Conceptual Model

In response to the context, problem statement, research objectives and research questions the conceptual framework is developed to illustrate the connections and interrelations between the topics (figure 1.2). It further illustrates how these connections relate to both the main research question and the sub-research questions.

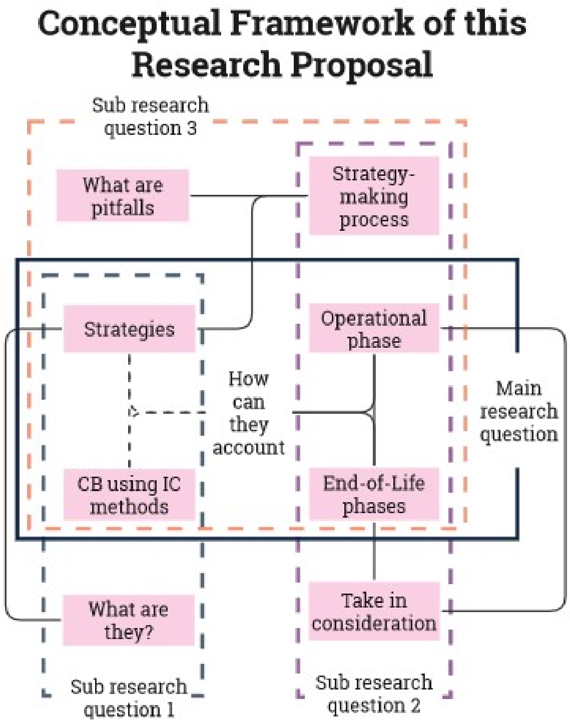


Figure 1.2: The conceptual framework of this research.

At the core of this research are the following four concepts *strategies*, the *Operational phase*, the *End-of-Life phase* and *Circular Building using Industrialised Construction methods*. To understand and grasp the core concepts the sub-research questions are formed to construct and develop knowledge. The first sub-research question revolves around the identification of applied strategies. The second sub-research question pivots around how the operational and End-of-Life phases are considered during the strategy-making process. The last sub-research question revolves around the existing pitfalls in strategies for the operational and End-of-Life phases of Circular Industrialised Construction buildings.

1.5. Societal and Scientific Relevance

This research is conducted because both in society and the scientific field of building sciences the notions of Industrialised Construction and circularity are gaining traction. In theory, the potential of Industrialised Construction compared to traditional construction lies in, improving efficiency, cost-effectiveness, quality control, safety, sustainability, and flexibility/customization in the construction process (Setaki & van Timmeren, 2022). Therefore, Industrialised Construction is predominantly used in serialized construction, particularly in housing, hotels, student accommodations, and healthcare facilities (Lawson et al., 2014). The sectors in the Netherlands that could benefit the most from the application of Industrialised Construction methods are currently faced with several challenges. Among others, there are shortages in labour, materials and rising costs in the construction sector. Additionally, the Netherlands is currently transitioning towards a circular economy.

1.6. Reading guide

Beyond this introduction, the report consists of 8 chapters. First, the theoretical background on the research topic of Industrialised Construction, Circular Building, Circular Industrialised Construction and other relevant topics are discussed. Next, chapter 3 describes the applied methodology for this research. Chapter 4 presents the first part of the research findings. In this part, the case study results will be presented. Furthermore, chapter 5 reviews the case study data through a within-case analysis. Chapter 6 presents a proposed framework that enables companies to apply the identified strategies to building specific parts. Furthermore, chapter 7 contains the discussion. Moreover, the chapter with the conclusion follows and lastly, a reflection on the research and graduation process will be given.

2

Theoretical Background

The goal of this chapter is to present the existing knowledge regarding Industrialised Construction and Circular Building. First the subject of Industrialised Construction(2.1) will be discussed. Then the theoretical background concerning Circular Building will be explained (2.2). In succession of this is the topic of Circular Industrialised Construction will be analysed in section2.3. Penultimate, the circular real estate management theories will be discussed in section 2.4. Lastly, the conclusion of the chapter will provide an overview of the theoretical background 2.5

2.1. Industrialised Construction

2.1.1. What is it?

The phrase Industrialised Construction has been prevalent in the Architecture Engineering and Construction sector since the end of the Second World War (McCutcheon, 1989). After the Second World War, mainland Europe was faced with an immense demand for housing. Several solutions were executed and Industrialised Construction was seen as an effort to increase the production of the construction sector (McCutcheon, 1989). With many different approaches across Europe to building housing solutions, many scholars began developing different terminologies describing Industrialised Construction (Lessing, 2006). Recently there have been several heated discussions about what Industrialised Construction encompasses. It is not the goal of this research to start another debate about the exact definition of Industrialised Construction in the literature. Therefore the phrase Industrialised Construction is considered a more holistic terminology that aims to improve the (resource) efficiency of the building process. A sub-sequential effect of this may be that the Built Environment's impact on the environment is reduced (Kedir & Hall, 2021).

What are all the different Industrialised Construction definitions proposed by these academics? Some make the argument that Industrialised Construction is the same as off-site production, Modular integrated Construction or prefabrication (Lessing, 2006). In his article Lessing (2006) argues that producing building elements on another location (off-site) than the location of the actual building (site) can be described as Industrialised Construction. An important aspect of this definition is the eight characteristics this type of Industrialised Construction should adhere to. Those characteristics are (1) Planning and control of the processes, (2) Developed technical systems, (3) Off-site manufacturing of building parts, (4) Long-term relations between participants, (5) Supply chain management integrated into the construction process, (6) Customer focus, (7) Use of information and communication technology & (8) Systematic performance measuring and re-use of experiences (Lessing, 2006). One aspect overlooked in Lessing (2006) definition and characteristics is the possibility that off-site manufacturing and construction can still adhere to traditional building methods, albeit in a different location (offsite) from the actual construction site. This implies that while these factors can collectively facilitate an improved industrial approach to the Built Environment through the assembly of buildings, a crucial objective for industrialisation is absent—specifically, the endeavour to enhance efficiency (Kedir & Hall, 2021).

There are several different approaches clients, contractors, architects and other stakeholders can achieve assembled buildings. The level of finishes and dimensions of these building elements can vary greatly. Lawson et al. (2014) describes various types of modular construction materials and elements that can be assembled on-site. They identify five classifications for building elements and recognize that building materials can also be fabricated in a factory setting. Thus the five classifications are **Materials**, **Components**, **Elemental or planar systems**, **Volumetric systems** and **complete building systems**. In addition, Lawson et al. (2014) acknowledges the possibility of combining several classifications in one building. Although these types are not per definition methods of Industrialised Construction. These prefabricated construction elements can be used as such if a certain degree of repetition or standardisation can be implemented(O'Connor et al., 2015).

Industrialised Construction is an effort to improve efficiency in the overall construction process. This results in efforts to implement standardisation in the building process to create resource efficiencies in the building process. Why are these standardisations and improvements in efficiencies necessary in the Built Environment?

2.1.2. Why does it offer a solution?

The Built Environment has been identified as a large contributor to the waste production and pollution of the Earth's environment. The waste production by the construction sector has been excessive, where 10 to 25% of materials that enter a construction site are reduced to waste(Ajayi et al., 2017). Additionally, several studies have shown a significant decrease in the efficiency of the construction sector over the last decades (Lim, 2021; Mohsen Alawag et al., 2023). This has supported the narrative that Industrialised Construction offers a solution to these perceived problems(Ajayi et al., 2017; Lim, 2021; Mohsen Alawag et al., 2023).

The application of Industrialised Construction is displayed as an increase in standardisation. This standardisation offers the sector the possibility to improve resource efficiency. The following resources have been identified as topics in which Industrialised Construction can create efficiencies: time management, material efficiency, Quality, Costs and safety. This results in overall improvements of cost-effectiveness and sustainability improvements(Mohsen Alawag et al., 2023).

On the subject of time management Industrialised Construction offers an improvement. Due to the construction process being transformed from activities in series to activities in parallel. Additionally, when works are being done for several buildings the delivery or availability of materials is less of an issue since these can be stored in the factory for several projects (Tsz Wai et al., 2023).

Standardisation offers the opportunity to improve material efficiency in the construction process. Knowledge about the construction activities that repeatably take place in off-site production sites allows for adjustments in the production materials and processes so that materials are used proficiently (GIBB & ISACK, 2001). In addition, when off-site productions can support a continuous production of building elements, the supply chain can become leaner in procurement. This allows for another sense of resource efficiency(Ferdous et al., 2019).

Producing building elements in a controlled factory setting creates an overall efficiency in the produced quality of the construction (Meiling, 2008). Not only are the elements no longer impacted by the elements. Thus the risk of materials being wet becomes less an issue. Productions taking place in controlled environments result in constant settings that create predictability in material responses(Meiling, 2008).

In addition to the quality improvements created by Industrialised Construction. It has also contributed to creating safer work environments for construction workers (Abas, 2015; Ismail et al., 2013). Besides moving several construction activities that rely on heavy machinery to a safer indoor environment. The application of Industrialised Construction is also stated as an improvement of the mental health of construction workers (Abas et al., 2018; Fagbenro et al., 2023).

Besides increasing the resource efficiency of the construction process. Industrialised Construction has also been identified as a method to increase the productivity of the construction process (Wang et al., 2020). The productivity of the construction sector has been lacking behind other industrialised sectors for a few decades (O'Connor et al., 2014). The positive effects of standardisation on productivity have been identified in several sectors. However the application of standardisation and thus Industrialised Construction has been lacking. Why is the application of Industrialised Construction obstructed?

2.1.3. What are barriers and challenges for this solution?

Although Industrialised Construction is resurfacing as a solution to previously described challenges, such as resource efficiency and decreases in productivity. In applying Industrialised Construction in the Built Environment several challenges and barriers remain standing(Wuni & Shen, 2020).

However, reviewing all existing barriers and challenges can be an overwhelming task. Therefore the most persistent barriers and challenges that still impact the application of Industrialised Construction are categorised and described. Those barriers and challenges are lack of design knowledge, supply chain management, Reluctance by the construction sector, and overlap between traditional construction and Industrialised Construction.

Lack of design knowledge has been widely described by actors in the construction sector as a limiting factor for the application of Industrialised Construction (Wuni, Shen, & Antwi-Afari, 2021). In the traditional building method *change orders* could usually be resolved on-site resulting in minor changes(Sun et al., 2020) to the building but resulting in higher waste production (Ghisellini et al., 2018). However due to the connecting details of prefabricated design elements everything in the design needs to fit together (Grüter et al., 2023). Inexperience in designing and preparing drawings to this level of necessary detail results in underwhelming rewards. As the costs of change orders to Industrialised Construction is significantly higher than traditional building. As a consequence of these higher costs the willingness to select Industrialised Construction as the construction method for the next project decreases(Charef et al., 2021).

The second barrier and/or challenge is the supply chain management necessary for Industrialised Construction. A benefit attributed to Industrialised Construction has been the option to construct elements in parallel with each other and parallel to the necessary groundwork's (Wang et al., 2020). This parallel approach results in time efficiency in the overall planning of construction activities. However, these benefits rely upon the delivery of prefabricated elements to the building site (Ajayi et al., 2017). Delivery delays can reduce the time efficiency created. Therefore Industrialised Construction relies more on Just-in-Time delivery of building components (Ajayi et al., 2017). Therefore the supply chain management of construction projects becomes a larger challenge than it already is. Since project timelines become more reliant on the delivery of building elements(Luo et al., 2019, 2020).

Many researchers have identified the construction sector as a conservative sector that is reluctant to change in general (Wuni & Shen, 2020). The sector also is influenced by large financial mechanisms that favour traditional and known solutions to problems (Wuni, Shen, & Osei-Kyei, 2021). This results in reluctance by the sector to adopt and change to a new construction method. The application of Industrialised Construction is hindered by this reluctance of the sector.

Finally, the last challenge/barrier that limits the application of Industrialised Construction is the overlap between traditional construction and Industrialised Construction on project sites. Although the modular design of elements combined with the off-site production allows for the majority of a building to be produced through Industrialised Construction (O'Grady et al., 2021). To some extent, the usage of traditional construction methods remains necessary. In particular, the groundwork on project sites can not be done in advance. Additionally, the finalising works on a building, usually consisting of works to the facade, are completed using traditional construction methods (Liu et al., 2019). These construction activities are planned well in advance and unexpected time efficiencies caused by the modular design can not be reaped. Thus creating friction between the contractor(s) and suppliers that work on these projects (Luo et al., 2019).

Many researchers have reviewed these challenges and barriers. These barriers can sometimes be part of large macroeconomic structures. Thus solving these barriers or challenges is a difficult problem that can be classified as a wicked problem. Therefore a single solution is often lacking. Thus the question remains: what can we do to subdue these barriers and challenges?

2.1.4. What mitigating strategies exist for these barriers and challenges?

With research into barriers and challenges for the application of Industrialised Construction, additional research in subduing these barriers and challenges has emerged (Hwang et al., 2018). As part of this research, several strategies to mitigate these barriers and challenges have been developed. Some of these strategies originate from other sectors where similar barriers and challenges exist(ed). Most of the mitigating strategies are already reviewed on their effectiveness on the barriers and challenges for Industrialised Construction (Hwang et al., 2018).

Reviewing all existing mitigating strategies for barriers and challenges for the application of Industrialised Construction can be an overwhelming task. Therefore the mitigating strategies for the barriers and challenges introduced in section 2.1.3 will be discussed. Those barriers and challenges are lack of design knowledge, supply chain management, Reluctance by the construction sector, and overlap between traditional construction and Industrialised Construction.

The lack of design knowledge with modular components that are produced using Industrialised Construction methods can be mitigated by developing new design philosophies (Grüter et al., 2023). Reviewing and rethinking the design process to assist the manufacture and assembly of buildings can mitigate the lack of design knowledge (Wuni, Shen, & Antwi-Afari, 2021). A focus on a new design philosophy such as Design for Manufacture and Assembly (DfMA) can reduce the lack of design knowledge and create more awareness among designers about the aspects that need to be taken into consideration (Gao et al., 2020).

The second barrier that needs to be overcome in the application of Industrialised Construction is supply chain management. With off-site production and modular elements, the integration of the supply chain becomes challenging. In particular the additional vertical and horizontal integration of these elements(Luo et al., 2019). Fortunately, these challenges have already occurred in different sectors. Thus the solutions can be tracked and implemented for modular building elements (Ajayi et al., 2017). Additionally, the reliance on Just-in-Time delivery has also been implemented in other sectors to improve efficiency(Ajayi et al., 2017). To implement Industrialised Construction the mitigating strategies concerning supply chain management can thus be reviewed and implemented from other sectors.

Introducing innovation is usually faced with reluctance by a sector. The reluctance to the application of Industrialised Construction is not different from other sectors. An often identified mitigating strategy to this reluctance is starting conversations and discussions with the sector (Luo et al., 2019). This is the start of creating acceptance and understanding of the problem. The next phase in mitigating the reluctance of the sector is creating ownership of the innovation among the sector (Van den Broek, 2020). Ownership of innovation can improve the acceptance and usage of innovations. In the Dutch construction sector, there has been a rise in usage of Industrialised Construction methods even by companies that hold a big share of the construction market (Koolwijk & Wamelink, 2023).

Finally, the mitigating strategy for the frictions between traditional building methods and Industrialised Construction methods consists of two factors. Building trust and experience between the different contractors involved in projects is one factor in mitigating this challenge (Lim, 2021). The other strategy is structuring the procurement and contractual agreements so they can specifically arrange flexibility between the different contractors (Straub et al., 2012).

2.1.5. Concluding Industrialised Construction

In conclusion of this section. Industrialised Construction can be described differently according to existing literature. For purposes of this research, the phrase Industrialised Construction is considered a more holistic terminology that aims to improve the (resource) efficiency of the building process. In practice, the application of Industrialised Construction comes down to constructing standardised modular building elements off-site that are assembled on the project site. While implementing Industrialised Construction several barriers and challenges have arisen. The most important barriers and challenges are the lack of design knowledge, supply chain management, Reluctance by the construction sector, and overlap between traditional construction and Industrialised Construction. In response several mitigating strategies have been devised. Those are new design philosophies such as DfMA for the designers of buildings constructed through Industrialised Construction, vertical and horizontal integration of the supply chain while also hitchhiking on existing solutions in other manufacturing sectors, Starting conversations with the sector over the benefits of Industrialised Construction and the last mitigating strategy is procurement procedures and contractual agreements that bridge the gap between traditional construction and Industrialised Construction.

2.2. Circular Building

2.2.1. What is it?

The concept of the Circular Economy in the Built Environment has long been around. Within the Built Environment the concept of a Circular Economy can be explained as efforts to reduce greenhouse gas emissions while creating urban areas that are more liveable, productive and convenient (The Ellen MacArthur Foundation, 2023). The reduction in greenhouse gas emissions can be achieved by reducing the energy consumption of the construction sector and re-using the construction materials. Thus creating a closed loop of building materials and products. The first example of loop thinking regarding resources related to the Built Environment is a report from 1976. This report was a reaction to the existing oil crisis(Stahel, 2020). Architects and engineers started to review the Built Environment to reduce waste and energy production. Initial findings suggested that re-using materials instead of recycling would economically make more sense(Stahel, 2020). This marked a transition in thinking from a Linear Industrial Economy towards a Circular Industrial Economy. This initial surge of interest was followed by a lack of action to transition towards a Circular Economy in the industry. The concept of the Circular Economy would remain popular in the academic community, outside of that it did not spark that much interest (Stahel, 2020). This was briefly interrupted in 2002 by the *Cradle-to-Cradle* concept of McDonough and Braungart (2003). But the big break for the Circular Economy came in 2010 with the start of the Ellen MacArthur Foundation and the development of the butterfly diagram (The Ellen MacArthur Foundation, 2023).

The butterfly diagram by the Ellen MacArthur Foundation envisioned 2 loops that need to be affected to implement the Circular Economy (The Ellen MacArthur Foundation, 2023). The green loop represents the biological cycle and the blue loop represents the technical cycle (figure 1.1). The biological loop is aimed at developing and designing materials that can regenerate in nature, are easily reused or supplement another biological loop(The Ellen MacArthur Foundation, 2023).

The Technical loop is aimed at reviewing design philosophies and manufacturing procedures. To rethink the biological loop the technical loop needs to produce solutions or other assembly procedures for the products they manufacture (The Ellen MacArthur Foundation, 2023). The Built Environment is affected by the technical and biological loops. Several materials used in the Built Environment are considered wasteful based on the co^2 production of these materials. Steel, Aluminium, Concrete and Plastics have been identified as a major polluting factor (Antonini et al., 2020). Therefore the technical loop needs to review the use of the biological loop in its design, manufacturing and disassembly cycle (O'Grady et al., 2021).

In practice, the Circular Economy in the Built Environment can be represented by two principles. The first principle is *designing for Disassembly* (Rios et al., 2015). Within Circular Building this can be measured by the level of reversibility. This means to what extent can connections between materials be reversed? A screw can be unscrewed and reused. Glue can be applied once and results in two materials that are harder to remove from each other (Antonini et al., 2020). The second principle is the material passports. This principle resolves around extensive supply chain management, where existing buildings are seen as a potential resource for new building projects (Soman et al., 2022). To sufficiently design new buildings with materials of existing building materials data needs to be collected to assess which materials can be reused (Soman et al., 2022). These two principles combined provide the Built Environment with a lot of data about the re-usability of existing buildings (Anastasiades et al., 2021).

2.2.2. Why does it offer a solution?

As mentioned before the Built Environment has been identified as a large contributor to the waste production and pollution of the Earth's environment (Adams et al., 2017). To reduce the environmental impact of the Built Environment the Circular Economy is considered an effective strategy to reduce the emissions of greenhouse gasses and prevent waste production (The Ellen MacArthur Foundation, 2023).

In practice, the process of Circular Building resolves around three topics. Reducing the emission of greenhouse gasses through carbon capturing in construction materials. Secondly, the reduction of waste in the construction process by reimagining the value of materials that previously would have been demolished. And lastly, reducing the overall energy consumption through the lifetime of a building.

During the production of construction materials, a significant amount of co^2 gasses are emitted

(Joensuu et al., 2020). To reduce the impact of this the re-use of these materials is considered an approach that prevents unnecessary co^2 production (Okorie et al., 2018). The chain of thought here is that by re-using construction materials the amount of co^2 that was emitted does not have to be emitted again.
In addition to that, the butterfly diagram and the impact of co^2 on the environment has resulted in a renewed emergence of wood as a construction material (Piccardo & Hughes, 2022). Due to the natural ability of trees to transition co^2 to oxygen, the usage of wood as a construction material is gaining traction. Wooden materials capture co^2 instead of producing these during the fabrication of construction process (Al-Mamoori et al., 2017). This can result in creating a net-equal or net-profit in co^2 production when constructing a building (Al-Mamoori et al., 2017).

As mentioned in section 2.1.2, 10% to 25% of materials used during construction end up as waste. Due to the butterfly diagram, the impact of waste on the biological and technical loop is more often taken into consideration (Osmani, 2011). This has resulted in efforts to reduce the production of waste during the construction process. This is achieved by reusing materials that would have been demolished in other buildings (Ferdous et al., 2021). This has resulted in re-imagining buildings as material banks. To sufficiently procure all these materials, databases are made of new and existing buildings. These databases or material passports create the ability for designers and architects to select their materials (Munaro & Tavares, 2021). Thus reducing the production of waste, since fewer materials need to be produced for the construction of a building.

Intending to reduce the co^2 impact of the Built Environment the insights about the energy production of buildings have resulted in new efforts to reduce the energy required for buildings (Al-Mamoori et al., 2017). Especially over a lifetime buildings require a considerable amount of energy for heating and cooling (Gupta & Tiwari, 2022). To close the loops of the butterfly diagram efforts are made to reduce the energy demanded for buildings. Reducing energy demands for buildings can result in a reduction of co^2 production (Gupta & Tiwari, 2022).

In practice, the application of the Circular Economy in the Built Environment can be expressed by the use of modular design. Here the first overlap between Industrialised Construction and Circular Building is visible. Since the same principles developed by Lawson et al. (2014) can be used for categorising components. These five classifications are: **Materials**, **Components**, **Elemental or planar systems**, **Volumetric systems** and **complete building systems**.

Circular Building offers the possibility to reduce the environmental impact of the Built Environment. As part of the circular approach the Built Environment is impacted through the re-use of materials, efforts to reduce the energy demand and material passports for the buildings. However, the application of the Circular Economy has been lacking. What barriers and challenges exist for the application of Circular Building in the Built Environment?

2.2.3. What are the barriers and challenges for this solution?

Since Circular Building is becoming a more accepted building method in the construction sector. In specific the application of material passports, re-use of materials and modular design. However, several barriers and challenges remain in place.

Highlighting all the existing barriers and challenges that are still in place for the application of Circular Building is almost impossible. Therefore the following barriers and challenges that mostly impact this are discussed and described here. Those barriers are a lack of design knowledge, reluctance by the sector to adopt, certifications on materials and existing building regulations and building codes.

In the process of designing for Circular Buildings the lack of design knowledge has been identified as a challenge for the application of the Circular Economy in the Built Environment (Rahla et al., 2021). This lack of design knowledge can be attributed to two factors. Firstly, the ability to start designing with existing construction materials. Instead of designing buildings to be constructed out of new materials (Grüter et al., 2023). The existing materials needed to be resourced to be integrated into the design. A result of inexperience in this method has resulted in underwhelming results, higher costs and delays in the construction process (Ghisellini et al., 2018).
The second factor impacting the lack of design knowledge is the realisation that new buildings need to be disassembled (Ferdous et al., 2019). This means that connecting details between every type of material has become an important aspect

of the design. A certain level of reversibility is desired in building elements. A lack of awareness or knowledge on that aspect can result in underwhelming experiences (Ferdous et al., 2019).

The second barrier that limits the implementation of the Circular Economy in the Built Environment is the reluctance of the sector to adopt and change to this new building method (Çimen, 2021). The Architecture, Engineering, Construction and Operation (AECO) industry is operating at a macro-system level. The introduction of adjustments to this system is often very difficult (Geels & Schot, 2007). Circular Building is a niche solution that needs to impact a macro-level system. This creates a change that is very incremental while these changes need to happen a lot faster (Çimen, 2021; Geels & Schot, 2007). Since there is no owner of the system it becomes difficult to adjust since the actors involved rely on each other (Leising et al., 2018).

In order for the financial sector to invest into Circular Buildings, the circularity needs to be quantified to a certain degree (Brown et al., 2016). This has resulted in several different types of certifications for buildings. These certifications are developed for different layers of the building (Pushkar, 2015). This results in certifications on building materials, energy demands, co^2 impact and several other aspects (Oskouei et al., 2020). All these different types of certifications pose a challenge. Considering which certification exists and needs to be applied impacts the efforts by designers to implement this (Pérez-Lombard et al., 2009).

The fourth and last barrier that impacts the application of Circular Buildings in the Built Environment is the existing building codes and regulations (Sparrevik et al., 2021). The reuse of existing materials and elements is often hindered by improvements made in the building codes. These improvements are often made to improve the quality of buildings (Foliente, 2000). However, these improvement limits the re-use ability of these materials and elements. As a result, certain materials or elements do not meet the requirements for new buildings (Akinade et al., 2020). Consequently, this impacts the application of Circular Building in the Built Environment.

To conclude, the application of Circular Building in the Built Environment is limited by several barriers and challenges. Those that impact Circular Building the most are a lack of design knowledge, the reluctance by the sector to adopt and transition towards Circular Building, the additional certifications necessary and the existing building codes and regulations. These barriers and challenges generate the question: "What can be done to mitigate these barriers?"

2.2.4. What mitigating strategies exist for these barriers and challenges?

Whenever research is done into barriers and challenges that limit the application of new technologies. There is often research into strategies that mitigate these barriers and challenges (Bajzelj et al., 2013). In reaction to the barriers and challenges introduced in section 2.2.3, strategies that mitigate these barriers and challenges are discussed.

This section discusses mitigating strategies for the introduced challenges and barriers. Just as it is near impossible to discuss all barriers and challenges, it is also difficult to discuss all mitigating strategies for these barriers and challenges. Therefore the most prevalent and relevant strategies are discussed. To reiterate, the mitigating strategies are developed for the following barriers and challenges: lack of design knowledge, reluctance by the sector to adopt, certifications on materials and existing building regulations and building codes.

The lack of design knowledge can be mitigated by new design philosophies. Several new design philosophies have been developed (Charter, 2018). The most noteworthy are; Design for Disassembly (DfDa) and Design for Deconstruction (DfDc) or a combination of the two Design for Disassembly and Deconstruction (DfDD) (Crowther, 2005; O'Grady et al., 2021; Rios et al., 2015). The difference between Disassembly and Deconstruction lies in the layer of the building. Deconstruction is more aimed at deconstructing the load-bearing structure of the building. Where disassembly is more centred around the disassembling parts for maintenance and repairs. In addition to these two philosophies, a third design methodology is emerging. Design from Disassembly (DfromD), which contains the method to design from the end-of-life of buildings (Grüter et al., 2023). Thus using the materials stored in buildings as resources for a new building (Anastasiades et al., 2021).
These new design philosophies can complement the existing design philosophies that promote modular design. An important part of the modular design philosophy is the deconstruction and

disassembly of a building (Rios et al., 2015). Modular design philosophies as previously discussed by Lawson et al. (2014) can contribute to an understanding of Circular Building.

The second challenge that needs to be overcome is the reluctance of the sector to adopt and change to a new method (Çimen, 2021). Reluctance has been a research subject in several other sectors. This macro-level barrier can only be mitigated when the system as a whole is taken into consideration (Geels & Schot, 2007). The suppliers of building materials are also part of the system. Therefore it is important to realise that the application of Circular Building is part of a system of system (DeLaurentis & Callaway, 2004).
To make adjustments to this, certain thresholds can be implemented (Giorgi et al., 2019). Requiring buildings to be disassembled to a certain percentage of volume increases the circular efforts. As well as requiring a certain percentage of used materials to be used in buildings. Organising these government-enforced certifications can incrementally increase the Circular Economy in the Built Environment (Munaro et al., 2020).

To implement these thresholds a challenge emerges. The challenge of the increasing certifications necessary for buildings to start development (Charef et al., 2022). All the different material components continue to require certification.

The last mitigating strategy addresses the barrier of the existing building regulations and building codes (Munaro et al., 2020). The sector is aware of this barrier. At the moment the chosen strategy is adjusting to the existing building regulations while also starting the conversation about adjustments to the building regulations (Çimen, 2021).

To conclude, the mitigating strategies that can be implemented for barriers and challenges that limit the application of Circular Building revolve around design philosophies and certifications, regulations and building codes. The most notable building philosophies are Design for Disassembly, Design for Deconstruction, Design for Disassembly and Deconstruction and Design from Disassembly. Certifications, regulations and building codes need to be developed and adjusted according to the developments of the sector.

2.2.5. Concluding Circular Building

In conclusion of this section, Circular Building can be described as efforts to reduce the environmental impact of the Built Environment. These reductions can be achieved by designing and building modular houses, reducing the energy demands of buildings, reusing materials in other buildings and making use of building materials that capture co^2. While implementing the Circular Economy in the Built Environment several barriers and challenges emerged. The most notable were lack of design knowledge, reluctance by the sector to adopt these new methods, additional certifications that are necessary and the current building codes and regulations. To mitigate these barriers and challenges several strategies have been developed. To address the lack of design knowledge several design philosophies have been refined: DfDa, DfDc, DfDD, DfromD. To address the certification requirements and building code and regulations changes necessary the industry has started discussing these with the corresponding authorities.

2.3. Circular Building and Industrialised Construction combined

2.3.1. Why does a combination offer a solution?

The concepts of Industrialised Construction and Circular Building offer the Built Environment the possibility to increase the resource efficiency and production capacity of the sector (Kedir & Hall, 2021; Sante, 2022). While also reducing the environmental impact and achieving set sustainability goals (United Nations, 2015). From both perspectives of Industrialised Construction and Circular Building the promise of a combination can produce lasting impact (Van den Broek, 2020).

This subsection discusses the similarities of both concepts and will conclude why these similarities supplement each other. First, the design phase and scope during the design process will be discussed. Secondly, the resource efficiency and waste reduction goals alignment of both subjects will be discussed. Lastly, the economy of scale benefits for the Circular Economy will be discussed.

Both Industrialised Construction and Circular Building require a different preparation and attention in the design phase in comparison with traditional construction (Abd Razak et al., 2022; Charter, 2018). In practice, the design of buildings constructed either through Industrialised Construction or Circular Building comes down to the use of modular design (Lawson et al., 2014). This can be achieved through different layers of the building, depending on the material, time in use and other factors (Davis & Gallardo, 2023). As a result the design phase of Circular Building and designing for Industrialised Construction is organised around a different design philosophy (Anastasiades et al., 2021; Crowther, 2005). The difference between the two topics relates to the design perspective. Design for Industrialised Construction is more guided towards the assembly and manufacturing process of a building (Gao et al., 2020). Where design for Circular Building is more aimed at the disassembly and deconstruction of a building (Akinade et al., 2020). A shift in design perspective is required for Circular Industrialised Construction. However the shift is not that enormous, it can be achieved by adjusting towards designs that can be disassembled (O'Grady et al., 2021).

Industrialised Construction is a holistic approach to improving the resource efficiency of the construction sector. The principles of the Circular Economy in the Built Environment are aimed at reducing the waste production of the construction sector (Ajayi et al., 2017). Both are aimed at properly evaluating resources and preventing waste production during the construction process (Ajayi et al., 2017). This alignment in evaluating resources properly offers the possibility to align overall efforts of implementing Industrialised Construction and Circular Building (Van den Broek, 2020).

With several sustainability goals that are set in the Netherlands and the EU, a Circular Economy approach to the Built Environment will be necessary to achieve these goals (Van den Berghe & Vos, 2019). With such a large quantity of buildings that need to be constructed, standardisation can be implemented to achieve cost-effectiveness (Trajković & Milošević, 2018). Standardisation and economy of scale benefits can be achieved by implementing Industrialised Construction methods (Trajković & Milošević, 2018).

To conclude Circular Industrialised Construction can offer a solution to the waste production, productivity decrease, energy consumption and co^2 production of the construction industry. Slight scope adjustments in the design process can transition a Circular Building of Industrialised Construction process towards a Circular Industrialised Construction. If a surge in Industrialised Construction and Circular Building can supplement each other the Built Environment has the potential to transition towards a functioning Circular Economy. Are there barriers and challenges that limit the application of Circular Industrialised Construction?

2.3.2. Barriers and challenges that exist for this combination and strategies to mitigate them

Barriers and challenges introduced in sections 2.1 and 2.2 can still exist for the combination of Circular Industrialised Construction. Most challenges and barriers exist for both topics (Charef et al., 2021; Wuni & Shen, 2020). This can be explained by a traditional perspective of the construction industry towards innovation and changes to the process (Çimen, 2021). In addition, this means that mitigating strategies developed for Circular Building and Industrialised Construction barriers or challenges can be implemented for the application of Circular Industrialised Construction

(Hwang et al., 2018).

This subsection does not only discuss the barriers and challenges for the application of Circular Industrialised Construction. In addition, mitigating strategies for these barriers and challenges will be explained. Additionally, some barriers and challenges that are specifically related to Circular Industrialised Construction will be discussed.

For the Circular Industrialised Construction process there is a lack of design knowledge which can lead to underwhelming results (Kanters, 2020). In efforts to mitigate this lack of design knowledge, several design philosophies have been developed. However, this *design for* approach lacks a combined effort to adjust to the lifetime of materials. Charef et al. (2022) argue therefore for a Product Service System that allows for adjustment to layers depending on the durability, aesthetics and use of the building services. In addition to this, they argue that an extended manufacturer responsibility system should be implemented. This allows for better tracking of the usage phase of buildings (Kanters, 2020).

For the application of Circular Industrialised Construction, the construction sector has been reluctant to implement this approach. This reluctance can be mitigated through several strategies. One of those is creating ownership of the application of Circular Industrialised Construction (Mohsen Alawag et al., 2023). This can be achieved through implementing new procurement and contracting methods. The application of for instance DBFMORE contracts can assure that the lifetime of buildings is taken into consideration and that stakeholders can be held accountable for later phases (Straub et al., 2012).

With the introduction of Circular Industrialised Construction in the Built Environment the possibility arises that elements between buildings can be swapped or changed (O'Connor et al., 2014). This means that there is a level of compatibility required among building elements. This requires coordination between designers, manufacturers and other stakeholders. At the moment the mitigating strategy is designing standardised elements (O'Connor et al., 2015). However, there is not yet a sector-wide standardisation in modular connecting details available (Anastasiades et al., 2021).

To conclude, several barriers exist for both Circular Building and Industrialised Construction that can also exist for Circular Industrialised Construction. Solutions that exist for Circular Building and Industrialised Construction can also be implemented for Circular Industrialised Construction. However new challenges and barriers also arise. The lack of a design philosophy that fits the entire lifetime of buildings and materials in a building is a challenge. A Product Service System can contribute to a lifetime design philosophy.

2.4. Other Theoretical Background

The combination of Circular Building and Industrialised Construction has created a new dynamic in the Built Environment. Circular Industrialised Construction is a new topic that requires research into all the phases of a building. Where adjustments in the design, manufacture and assembly of these buildings can be minor, but necessary. Research has been done in these specific phases. However, a subject that has not yet been researched is the operation and end-of-life phase of Circular Industrialised Construction buildings.

For the operation and end-of-life phase of buildings existing Real-Estate Management strategies can be implemented for Circular Industrialised Construction. There exist a lot of Real-Estate Management strategies and theories that can be applied to buildings. However, the decision is made to discuss the Shearing Layers Concept developed by Duffy (1990).

2.4.1. Shearing Layers of a Building

Frank Duffy is widely considered the developer of the shearing layer concept (Duffy, 1990). This concept revolves around the principle that buildings are a set of components that evolve in different timescales. The Shearing layers are Site, Structure, Skin, Services, Space Plan and Stuff (Figure: 2.1).

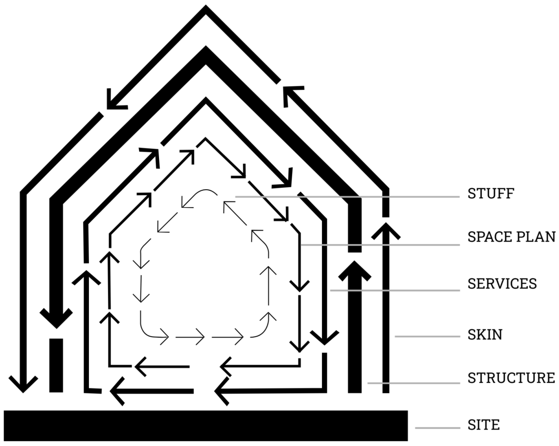


Figure 2.1: The concept of the building layers, introduced by Duffy (1990)

The different layers correspond to different objects and possible interventions in a building (Pushkar, 2015). Figure 2.2 highlights the different timescales and components associated with the different layers. Awareness of these different layers affects the design and therefore the maintenance strategies. Design choices affect the timescale of materials and their ease of repair (Davis & Gallardo, 2023). Awareness of the existing layers can supplement choices that result in modular buildings.

Building Layers	Timescale	Components
Site	Eternal	Excavation and landfill
Structure	30 to 300 Years	Foundations, columns, beams, and ceilings
Skin	20 Years	External walls, external wall covering, roof, and glazing
Services	7 to 15 Years	HVAC, electrical fixtures and plumbing fixtures
Space Plan	3 Years	Partitions, floor coverings and doors
Stuff	Daily to Monthly	Computers, printers, furniture and lamps

Figure 2.2: The different timescales of the building and the relation with the different elements (Duffy, 1990)

The consequence of the different timescales is the necessity to replace elements in the building at different rates (Duffy, 1990). This emphasizes the need for a modular design approach. So that elements that require replacement don't impact other layers that do not yet have to be replaced (Duffy, 1990).

2.5. Conclusion of the Theoretical Background

To conclude this chapter. A lot of theoretical background has been discussed. But the key takeaways from reading this chapter should be the following. Additionally, the key takeaways per subchapter are presented in figure 2.3

For this research, the phrase Industrialised Construction is considered a more holistic terminology that aims to improve the (resource) efficiency of the building process. In practice, the application of Industrialised Construction comes down to constructing standardised modular building elements off-site that are assembled on the project site.

Circular Building can be described as efforts to reduce the environmental impact of the Built Environment. These reductions can be achieved by designing and building modular houses, reducing the energy demands of buildings, reusing materials in other buildings and making use of building materials that capture co^2.

Circular Industrialised Construction can offer a solution to the waste production, productivity decrease, energy consumption and co^2 production of the construction industry. Slight scope adjustments in the design process can transition a Circular Building of Industrialised Construction process towards a Circular Industrialised Construc-

Summary of the Theoretical Background

Theoretical Concepts	Section	Summary
Industrialised Construction	What is it?	Industrialised Construction is considered a more holistic terminology that aims to improve the (resource) efficiency of the building process.
	Why does it offer a solution	In practice the application of Industrialised Construction comes down to constructing standardised modular building elements off-site that are assembled on the project site.
	What are barriers and challenges	The most important barriers and challenges are the lack of design knowledge, supply chain management, Reluctance by the construction sector, overlap between traditional construction and Industrialised Construction.
	What mitigating strategies exist for these barriers and solutions	Design philosophies such as DfMA for the designers of buildings constructed by means of Industrialised Construction, vertical and horizontal integration of the supply chain while also hitchhiking on existing solutions in other manufacture sectors, Starting conversations with the sector over the benefits of Industrialised Construction and procurement procedures and contractual agreements that bridge the gap between traditional construction and Industrialised Construction.
Circular Building	What is it	Circular Building can be described as efforts to reduce the environmental impact of the Built Environment.
	Why does it offer a solution	These reductions can be achieved by designing and building modular houses, reducing the energy demands of buildings, reusing materials in other building and making use of building materials that capture co2.
	What are barriers and challenges	Lack of design knowledge, reluctance by the sector to adopt this new methods, additional certifications that are necessary and the current building codes and regulations.
	What mitigating strategies exist for these barriers and solutions	To address the lack of design knowledge several design philosophies have been refined: DfDa, DfDc, DfDD, DfromD. To address the certification requirements and building code and regulations changes necessary the industry has started discussing these with the corresponding authorities.
Circular Industrialised Construction	Why does a combination offer a solution	Industrialised Construction and Circular Building are aimed at properly valuating resources and preventing waste production during the construction process (Ajayi et al., 2017). This alignment in valuating resources properly offers the possibility to align overall efforts of implementing Industrialised Construction and Circular Building (Van den Broek, 2020)
	Barriers and challenges for this combination	The lack of a design philosophy that fits for the entire lifetime of buildings and materials
	Mititgating strategies for these barriers and challenges	A Product Service System can contribute to a lifetime design philosophy.
Other Theoretical Background	Shearing Layer Concept	The Shearing Layer Concept revolves around the principle that buildings are a set of components that evolve in different timescales. The Shearing layers are: Site, Structure, Skin, Services, Space Plan and Stuff

Figure 2.3: A summary of the theoretical background order by section and subsection

tion. If a surge in Industrialised Construction and Circular Building can supplement each other the Built Environment has the potential to transition towards a functioning Circular Economy.

3

Methodology

This chapter provides a description of the research methods employed for this research.

3.1. Research Questions

To reiterate, the main research question of this research is: **How can strategies for circular buildings using industrialised construction methods account for the operational and end-of-life phases?** The sub-research questions that supplement the main research question are:

1. *What strategies for Circular Building using Industrialised Construction methods can be identified?*

2. *How are the operation and End-of-Life phases taken into consideration during the strategy-making process?*

3. *What are the pitfalls in the strategy-making process for the operation and End-of-Life phase of circular buildings using industrialised construction methods?*

3.1.1. Relevance

There are several new circular projects developed in the Netherlands and abroad. These projects typically consist of single, one-off lighthouse buildings that demonstrate the potential of existing buildings as material banks. Preparations in the design phase are required for these circular projects, including researching the degree of disassembly of existing building materials (Lawson et al., 2014). Lessons learned from these projects are for example a transition towards different construction details, such as the connections between walls, floors and roofs. Where these connections used to be "wet", they are becoming increasingly more "dry". Allowing for easier disassembly.

However, these circular efforts are not commonly applied to large-scale, serialized construction. Similar to circular projects, serialized construction also requires preparation in the design phase to avoid delays and cost overruns during construction (Enshassi et al., 2019). Several companies are exploring the combination of Industrialised Construction and Circular Economy in their building processes, developing a business case around prefabricated elements produced in a factory and assembled on-site.

Therefore this research is relevant for the scientific community because there is a new application of an existing technology that enables the construction sector to improve its efficiency and also enable a more circular built environment. Understanding the strategy nuances, boundary conditions for its application and pitfalls related to the application of a circular Industrialised Construction can benefit society in closing the loop of the circular economy. Thus reducing the construction sector's impact on the environment.
To clarify, the scope of this research is aimed at an industry-wide scale review of circularity efforts in the Industrialised Construction sector. Several companies are reviewed for their efforts to present a comprehensive overview of the efforts on an industry-wide scale.

3.2. Research Methods

3.2.1. Overall Approach

The selection of a comparative case study is a deliberate and effective choice for researching the operation and end-of-life strategies associated with circular buildings. This methodology allows for a detailed exploration of diverse cases,

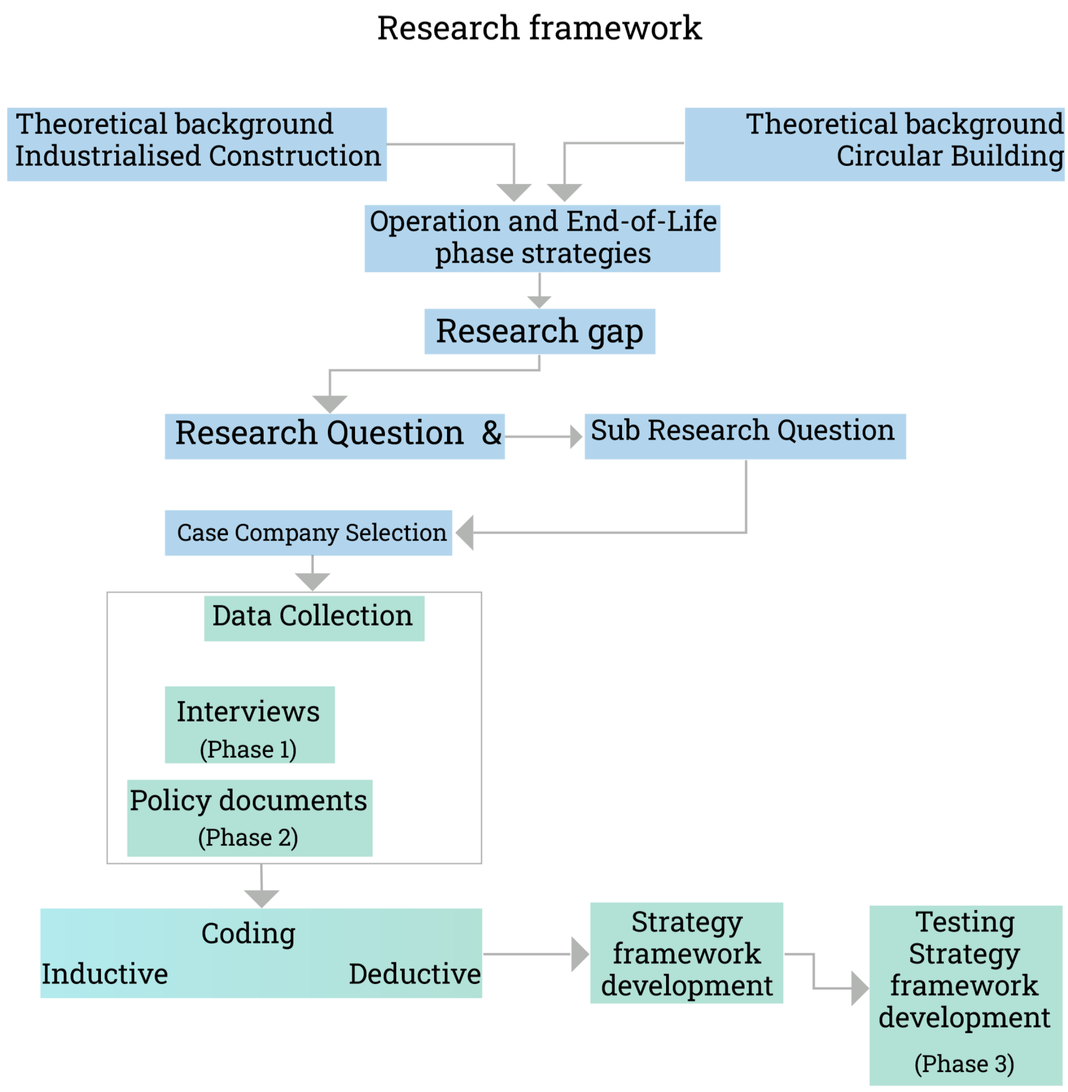


Figure 3.1: The research framework for this research, own work

enabling an understanding of how circular buildings, developed using IC, navigate operational challenges and approach end-of-life considerations. By comparing diverse examples, this research approach enables the identification of best practices, challenges, and innovative solutions, offering a holistic view of the intricate relationship between IC and sustainable building practices (Eisenhardt, 2021).
The research framework, derived from the conceptual framework, research questions, sub-research questions, and the chosen research method, provides a structured guide to this research. This overview encapsulates key elements, presenting a structured overview of research phases, data collection, and coding approaches (figure 3.1).

3.2.2. Case Company Selection

The case companies are selected on two overarching criteria. The first criterion is the application of Industrialised Construction methods for the manufacturing of their buildings. The case companies are selected on the basis that both planar and volumetric elements or components are manufactured in an off-site factory location. The second selection criterion relates to the efforts the case companies dedicate to circularising their buildings. The case companies are selected based on the appearance of phrases regarding circularity on their project web pages.

In addition to the 2 main criteria, several additional criteria were developed to ensure a diverse selection of case companies. This case study design, polar types, was selected to gather diversifying data(Eisenhardt, 2021). The first additional criterion is the typology and morphology developed by the companies. The criterion aims to diversify the functional typology and morphology of the buildings. The strategies between high-rise buildings and low-rise buildings presumably can vary. To diversify the functional typology, case companies were selected based on the building functions they developed—for example, rental housing (social housing or free market), owner-occupied homes or hospitality facilities. The third selection criterion is the type of elements or components that the companies develop. For instance, do they develop volumetric planar modules or components? Since differences between volumetric and components require differentiating strategies for design, manufacturing and assembly. The last additional criterion is the property rights of the companies after completion of the building. For example, are the companies owner/occupier, and owner/housing agency, do they sell the real estate after completion or are they only a developer of the structures?

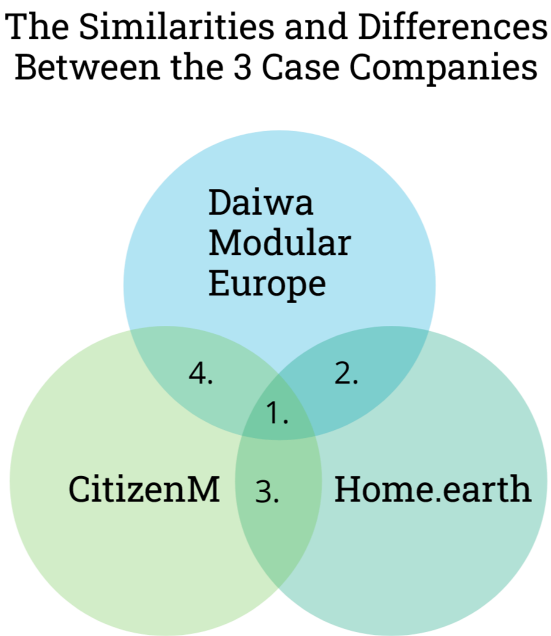


Figure 3.2: Structure in the coding

To conclude figure 3.2 illustrates the similarities and differences between the three selected case companies, Home.Earth, Daiwa House Modular Europe and CitizenM. Based on the boundary criteria three companies have been selected that engage in Industrialised Construction methods and Circular Building design (1). Two of the companies develop mainly housing solutions (2). Two of the companies are also owner/developer of the buildings once they have finished construction (3). And lastly, two of the companies develop only volumetric components.

Data collection

The 3 phases of the research

	Phase 1	Phase 2	Phase 3
Data collection method	Transcript's of interviews and site visits/ factory tours	Participatory observations and reviewing strategy & policiy documents	Transcripts of focus group session
Coding	Inductive		Deductive
		Optional	

Figure 3.3: The three Phases of Research

The data collection was planned to be carried out in three phases, with the possibility of not executing the second and third phases depending on the available time for research completion and the willingness of the case companies to share the required documents (figure 3.3).

	Citizen M	Daiwa Modular Europe	Home.Earth
Design	X	-	X
Development	X	X	-
Project management	X	-	X
Sustainability	X	-	X
Customer Relations	-	X	-

Figure 3.4: Overview of interviewees of all the selected case companies

The data collection for the first phase took place in the form of semi-structured interviews with employees of the case companies. The data was collected in the Autumn of 2023. Figure 3.4 illustrates the different departments that were interviewed. To protect the identity of the interviewee their job descriptions were generalised to categorise them.
The semi-structured interviews discussed a few topics, those were; lessons learned in applying Industrialised Construction and Circular Building, involvement during operation & maintenance phase, incentives for applying Industrialised Construction in Circular Building, circular assurance

after transition of ownership and storage of circular/modular design plans. As part of the interview process informed consent forms, and interview topics were shared at least 1 day before the start of the interview.
Depending on the availability of the interviewee and the researcher the interviews were executed either onsite in the offices of the case companies or through the online meeting software Microsoft Teams. To comply with the General Data Protection Regulation (GDPR) of Delft University of Technology.
Additionally, after the interview with an employee of Daiwa Modular Europe a site visit was executed. During this visit, several assembly lines for prefinished prefabricated volumetric components were examined. Several photos taken during this visit appear throughout this research report.
The companies were not comfortable with sharing policy documents, minutes of assemblies and other internal documents. As a result, phase 2 was not executed. Additionally, phase 3 was not executed as a result of the limited time available.
The data of the collected interviews is presented in the following chapters as a number between square brackets. Each number corresponds to an interview with an employee of one of the case companies. The relation between the number and interviewee can be found in Figure 3.5.

3.2.3. Data Coding and Analysis

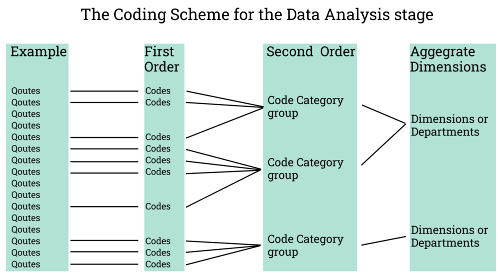


Figure 3.6: Structure in the coding

The comparative case study method enables a systematic comparison of strategies for circular buildings constructed through Industrialised Construction. The selection of case companies is based on their likelihood of having developed strategies for the operation and end-of-life phases. Analyzing similarities and differences across cases enhances theory building. The method underscores explicit theoretical arguments supporting the likelihood of specific strategies between different phases. The goal of the analysis is to identify fits, recognising that perfection is rare. The high fit often results from conceptualization and abstraction in defining and grounding the research. The method focuses on developing and defining strategies and approaches during the analysis (Eisenhardt, 2021).

Interviewees		Reference
Company	**Date**	**number**
CitizenM 1	September 26 2023	[1]
CitizenM 2	September 28 2023	[2]
CitizenM 3	September 28 2023	[3]
CitizenM 4	October 13 2023	[4]
CitizenM 5	October 13 2023	[5]
CitizenM 6	October 24 2023	[6]
CitizenM 7	October 24 2023	[7]
Daiwa Modular Europe 1	October 17 2023	[8]
Daiwa Modular Europe 2	October 17 2023	[9]
Daiwa Modular Europe 3	November 2 2023	[10]
Home.Earth 1	October 5 2023	[11]
Home.Earth 2	October 12 2023	[12]
Home.Earth 3	October 12 2023	[13]
Home.Earth 4	November 6 2023	[14]

Figure 3.5: Structure in the coding

4

Within-Case Analysis

4.1. Citizen M

4.1.1. The Story of CitizenM

The hotel room of a newly built CitizenM hotel has changed drastically in comparison to when they opened their first hotel in 2009 (figure 4.2). An important enabler in implementing improvements in the hotel rooms has been the interpersonal relations between the different departments. ”If a decision I made makes the job of the person across my desk difficult then they are going to tell me I made a mistake” [3]. Realising and being made aware that decisions in the design impact coworkers creates incentives for employees to consider different perspectives. This creates a culture that values the input of coworkers who operate in a different department.

The modular ability of the building is seen as a method to potentially relocate buildings on a new site. ”If it were not for building codes and regulations we could pick up every room of a hotel on the west coast of the USA and move it to a new hotel site in Germany, the only thing that would need to be adjusted is some reinforcements that are in place for earthquakes”[3] (figure 4.3). Not everyone within CitizenM thinks the relocation of a building is that easy. ”It is impossible to switch hotel rooms around between different building sites, not only because of the regulations but also because each room has different dimensions and can handle different loads. We would never relocate for instance our Rotterdam Hotel to London.” [6]. This further solidifies the assumption within CitizenM that the aim of Circular Building is mostly focused on different layers of the building.

Circularity within CitizenM is not only seen as the ability to configure the building modular. Circularity can be applied to several building layers at once. Where the modular ability of the hotel rooms is closer related to the structure of the building; furniture, headboards, flooring and light fixtures can also be sourced circular. ”If suppliers offer the option of re-usage, refurbishments and replacement of elements and components then we enforce this through our contracts with them”[2]. An important part of enabling the circular efforts of CitizenM is integrating responsibility into the supply chain.

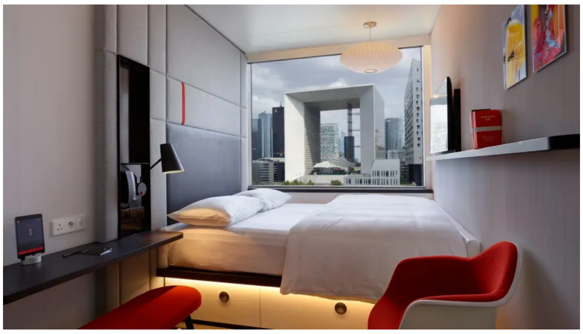


Figure 4.1: The hotel rooms of CitizenM as they are advertised at their website(CitizenM Hotels, 2023)

Due to visualising the hotel rooms as a combination of different elements, they have introduced improvements on an element basis. ”We’ve recently introduced shower-pods made of PET-G plastic, once they need to be replaced they can be easily circulated into the supply chain”[1],[4]. Thus slow but steady transition the hotel rooms to more sustainable and circular versions. ”I think one of my colleagues made a judgement call with the shower pods, he made a concrete cast for the new shower pods. In ten to fifteen years, when they need to be replaced, someone will be very unhappy about that” [3]. Although efforts are

Figure 4.2: An example of the building CitizenM builds and designs. This is their first hotel, Amsterdam Schiphol Airport (CitizenM Hotels, 2023)

Figure 4.3: An example of the building CitizenM builds and designs. This is Austin Downtown (USA, Texas)(CitizenM Hotels, 2023)

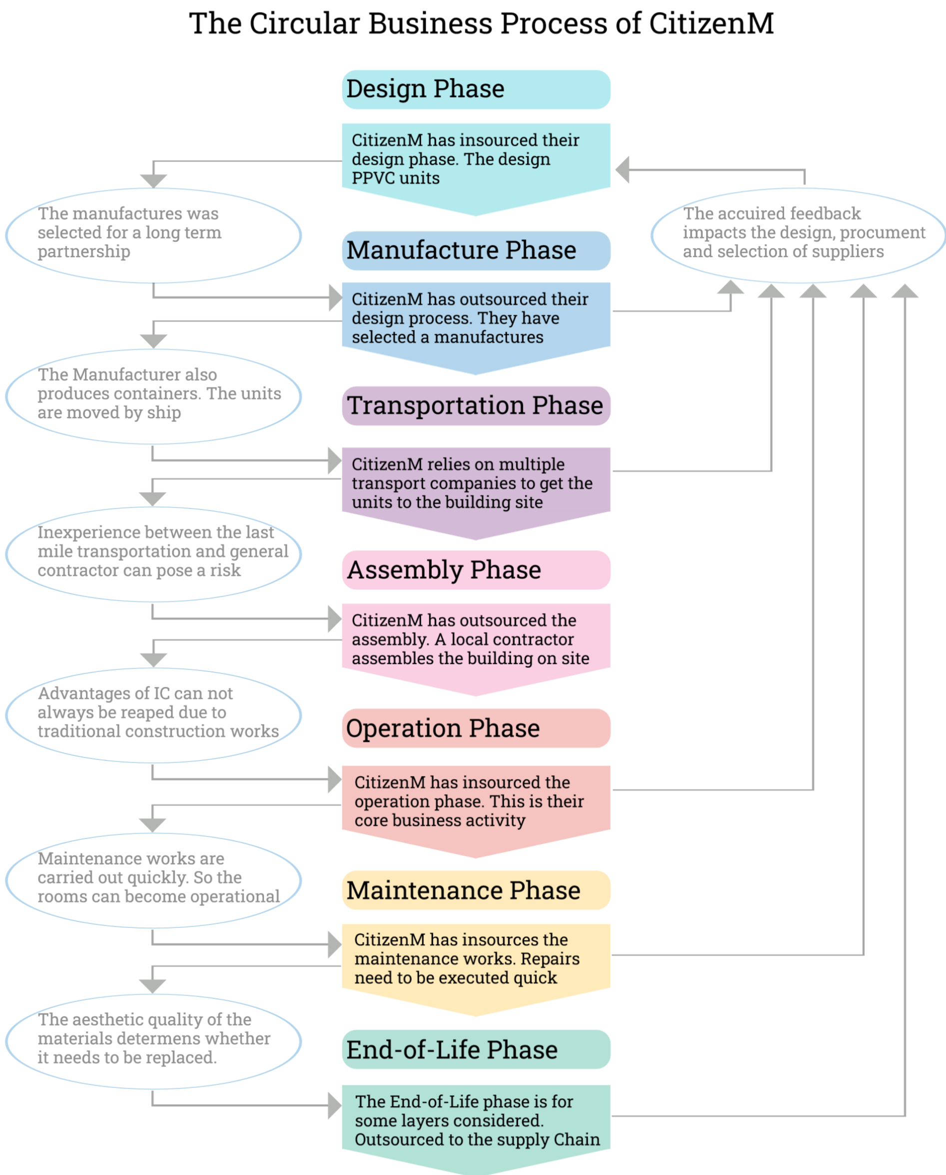


Figure 4.4: This is not the business model. It more shows the circular business process.

made in the company, the adoption and mindset of the company are sometimes still lacking.

The Case for Industrialisation

For both the traditional build and the modular build hotels, the rooms are all fabricated from standardised elements. ”Standardising everything makes everything about the repairs easier” [4]. ”Deviations in the standardisation are killing the business case”[1]. Replacing elements like ceiling tiles that are all the same size, dimension and material becomes a trivial job in the refurbishments of hotels. ”It is very understandable to give a guest 3 centimetres more in a room, but in the operation, this means that we now have two different types of everything” [5]. Slight deviations of just a few centimetres per hotel room become meters when hotels have 200 to 300 rooms. It also requires more resources because there is now a need for additional materials that need to be used for replacements.

4.1.2. The Circular Business process

When a new hotel is designed that will be constructed modular the lobby and living room are designed to be constructed traditionally. However, the hotel rooms and the corridors connecting them are produced off-site. ”An important factor for developing modular is the speed, time is everything for us” [1]. Once the hotel is finished and the operational and maintenance department takes over

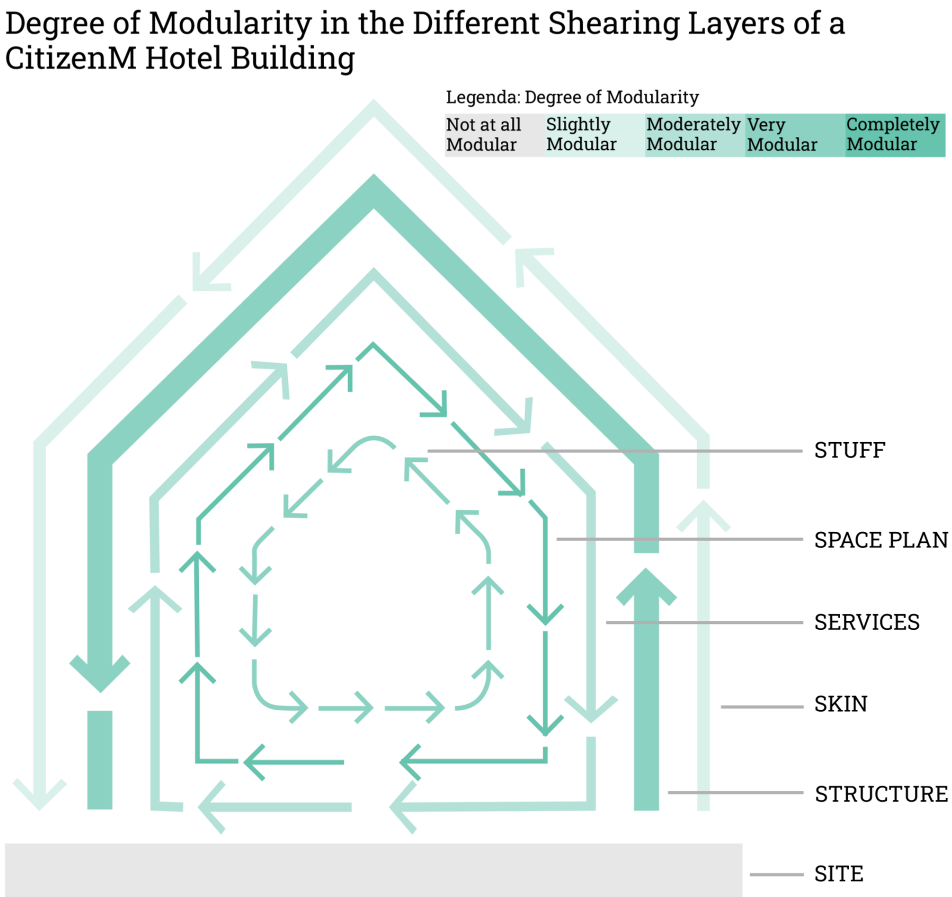


Figure 4.5: Degree of Modularity in the Different Shearing Layers of a CitizenM Building (Own work based on Duffy (1990))

feedback can be collected and distributed back into the design and construction phase. Thus creating iterations on the hotel rooms that impact not only the guests but also the maintenance, design and construction departments within the hotel chain. This is illustrated in figure 4.4

The circular business process of CitizenM starts at the design phase. In this process, the decision to build traditional or modular is made. This starts the development of the design plans for the overall hotel. "The decision to build modular and the cost-benefit this produces are considered very early on in our process. If you then consider that a modular hotel saves us around 1 million a month and the fact that a modular hotel is built 3 months quicker you can understand our preference" [1]. Once the decision is made to construct the hotel with modular units, the height and strength of every unit are calculated based on the building codes, building regulations and characteristics of the project site. "The building height and thus how many floors, thus rooms we can fit in a hotel is the biggest deciding factor for the height of our units." [6]. In the end, the amount of rooms that fit the site is the deciding factor for the development of a hotel.

The manufacturing process of the hotel rooms occurs simultaneously as when all the other works on site occur. "Once we get a green light for the hotel from the city council and our investors we start with the groundworks and the production of the hotel units by the manufacturer in China. This can happen all at once in parallel to each other. " [7]. "The hotel rooms are sealed by the manufacturer and transported by ship and road to the hotel site."[1]. After manufacturing the units are transported to the site and then assembled on the location. After the facade has been constructed through traditional construction, CitizenM takes ownership back and starts preparing for the operation. During the operation phase of CitizenM hotels, the materials in the rooms and lobby are faced with a significant amount of wear and tear. Together with expected and scheduled maintenance works a feedback loop is created between the different departments of the CitizenM and their suppliers. "We only work with suppliers that abide by our predetermined sustainability standards." [2]. By cooperating with sustainable suppliers feedback loops are used to modularise hotel rooms even further. "We update our brand standards every quarter, so planned repairs and refurbishments are executed and if necessary upgraded to the current brand standard" [2], [5]. Due to the need for replaceability within hotel rooms, the updated brand standards allow for improvements in the iterations of the modules.

Within the CitizenM departments there are some debates over the possibility of relocation of the hotel rooms. "We can pick up our hotel room in San Francisco and relocate it to Germany" [3]. Other departments were not so convinced. "I think it is impossible to relocate for instance the London Hotels, no place will suffice because of very strict building codes. (...), and building a new hotel will always be beneficial because it allows us to optimise the existing building regulations. "[6], [7]. This supports the vision within CitizenM that circularity can be achieved within several layers of a hotel.

4.1.3. Shearing Layers of Circularity

Due to the adaptability, timescale and expected durability of certain elements in buildings and subsequently the design, operation, maintenance and end-of-life strategies can be reviewed by using the shearing layers concept. This section contains an overview of the modularity of the different Shearing layers of modular buildings (Duffy, 1990). First, the *Site* layer will be briefly mentioned. Then the order in which the layers will be discussed and classified is *Structure*, *Skin*, *Service*, *Space Plan* and *Stuff*.

The *site* layer will not be discussed and reviewed since this section is still produced by traditional construction methods and therefore is outside of the scope of this research(Therefore the *site* layer is coloured grey in figure 4.5). This layer is therefore determined to be *Not at All Modular*.

The *Structure* layer of the hotels can be described as very modular. They can conveniently be picked up and relocated to another site. "The hotel room structure is a shipping container frame with openings for windows and the corridor" [3]. This stacking ability allows for the hotel rooms to be picked up and relocated to a different site. Depending on the height of the new building the structural strength of the rooms needs to be assessed to decide on which layer the room can be rebuilt. "The hotel rooms that are on the top floors of our Seattle or New York hotels can not be on the bottom of a similar hotel. They simply do not have the structural strength to support that." [3]. Therefore the *Structure* layer is considered to be *Very Modular*.

On the layer of the *Skin* of the building, the CitizenM hotels don't have that much modularity. "the finishing and facade of our buildings are always completed by traditional construction, we expect the facade to be there for over 60 years" [1]. The facade elements are clicked into position and can be disassembled but that is not an element that CitizenM is concerned about. "The reason for completing the facade by traditional construction is the aesthetic finish of the facade. It covers all the seams between the different units and unifies the entire building into one" [1]. Therefore the *Skin* layer is considered to be *Slightly Modular*.

The *Service* layer of CitizenM hotels does adhere to a certain degree of modularity. The modular application of this layer in the hotel rooms has frequently been reviewed by the design team. "Our shower pods have gone through a transformation since our first hotel at Schiphol, from unique oval-shaped towards rectangular shapes made from PET plastics"[4],[6]. The replaceability of elements in rooms has become a great incentive for certain design choices. Where the speed of replacement is essential (figure 4.6). "Every day a room is *out-of-order* that rooms cost us money, so repairs and maintenance must be done fast" [1]. Therefore the *Service* layer is considered to be *Very Modular*.

The *Space Plan* layer of CitizenM hotels is modular by design. The dimensions and floor plan of the hotel rooms are developed. "We won't change the floor plan of our rooms anymore, the composition of the bed, closet, bathroom and kitchenette area maximises the available room." [4]. In addition, there are return arrangements in place with several suppliers. Based on these arrangements the design and connecting details have been changed. From glueing floors to the structural layer, a clicking system has been introduced. Allowing for the disassembly of particular flooring panels. "We were initially surprised by the ability of our guests to completely vandalise a hotel room, we then started to vandal-proof them. The ability of our hotel guests to vandalise a room has us also made aware of the fact that a floor should be repaired by the panel. Previously we would have to replace the floor on the entire storey, now we just click out a panel and replace it with a new panel. The old panel can be sent back to the supplier and they re-purpose it" [1]. The *Space Plan*

Figure 4.6: An example of the room of a CitizenM hotel (CitizenM Hotels, 2023)

layer of CitizenM hotels can be categorised as *Completely Modular*.

The last layer, or the *Stuff* layer is by arrangement with suppliers also modular. ”Sustainability comes back in every aspect of our hotels, so we are starting to make sure that all sorts of items become circular, from the mattresses in the rooms to our furniture in the lobby. We have started with the furniture in the lobby, that is the first element that needs to be refurbished” [2]. Not all products are already modular or circular, but CitizenM is making efforts along its entire supply chain to make sure that products are as sustainable as possible. Therefore the *Stuff* layer can be categorised as *Very Modular*

Figure 4.7: Once the volumetric units are manufactured they are stored on the site (Own work))

4.2. Daiwa Modular Europe

4.2.1. The story of Daiwa Housing Modular Europe

The story of Daiwa Modular Europe starts forty to fifty years ago, when Jan Snel started converting shipping containers to construction site offices. Over the years the dimensions of a shipping container are carried over to other buildings that are produced by Jan Snel. The Daiwa Modular Europe group consist of three divisions. Jan Snel, the temporary housing solutions provider (Buildings are on the project site for 2 to 5 years), Medex, the modular medical building provider and Daiwa, the modular dwelling provider (figures 4.8 4.9).

Due to working with predetermined dimensions Daiwa Modular Europe can customise the elements that make a module. ”Our expertise today in modular housing stems from our heritage in the temporary structures we’ve built” [8]. This ability allows them to make iterations on modules (figure 4.7). ”The modules have such a degree of *losmaakbaarheid (releasability)* (level of reversibility) that nothing has to be demolished [...] the steel, wooden frames and windows can all be disassembled.” [9]. The reversibility of the modules is achieved due to the method of assembly. This allows Daiwa Modular Europe to implement methods to re-use existing building materials in new modules.

Daiwa Modular Europe is mostly a developer of buildings, they do offer maintenance packages to the organisations that own these buildings. ”The service level agreement determines the level of maintenance we offer to these clients” [8]. In the experience with clients and suppliers, they have optimised the floor plans of the modular building to create layouts that prioritise the efficiency of maintenance works. ”Clients usually demand that certain technical systems are accessible even when tenants are not home” [8]. These iterations have happened a long time ago, within Daiwa Modular Europe there is no one with an exact recollection of how these changes have occurred.

Due to the level of reversibility of the buildings they retain a certain value when a building needs

Figure 4.8: An example of a modular building developed by Daiwa Modular Europe. This project contains care apartments (Daiwa Modular Europe, 2023)

Figure 4.9: An example of a modular building developed by Daiwa Modular Europe. This project is housing for seasonal workers. (Daiwa Modular Europe, 2023)

to be moved. "We got a call to check out a certain building if it was built by us [...] it wasn't. But another party [...] bought this building because it could easily be adjusted due to the level of reversibility"[9]. Additionally, Daiwa Modular Europe has started implementing a *statiegeldregeling*[1] for their buildings. "If we know beforehand if a building needs to be (re)moved in 15 to 20 years we usually include a deposit arrangement in the contract" [8]. The practice of deposit arrangements helps in the integration of a circular economy. Since the buildings are after their lifetime taken back into the supply chain.

The case for industrialisation

An important aspect for Daiwa Modular Europe to build their modules in factory settings is mainly the efficiency of the process. It creates cost-effectiveness improvements. Another benefit of industrialisation is employee satisfaction. "All our employees can get here by bike, car or public transport, they don't waste time travelling to new construction sites every week."[8]. The decision to construct modules in the factory stems from their heritage, which required heavy machinery. With more than 20 production halls that produce a unit every 1 hour. The overall production of Daiwa Modular Europe is thus quite significant.

4.2.2. The Circular Business Model

Within Daiwa Modular Europe the decision to develop projects is related to the financial prospects and to what degree the modularity of buildings is taken into consideration. "We usually only react to tenders if the MPG[2] is set at 0.7 or lower, otherwise, we can't compete with traditional builders" [9]. The MPG value is an important deciding factor for Daiwa Modular Europe, to compete with traditional contractors the value needs to reach a threshold of at least 0.7.

The design phase of Daiwa Modular Europe buildings starts with the engineering department. "Depending on the required material used in the building the engineers start the calculations for either a steel, concrete or wooden frame."[9]. The overall design aspects are not yet standardised. Depending on the requirements of the client the dimensions of the bathroom and kitchen can change. "We have the floor plan of our units pretty much figured out, the bathroom goes left when you enter, the kitchen is on the right and then on the other side you have the windows" [10]. Due to the sheer size of the production capacity of Daiwa Modular Europe the layout of the modular rooms are already optimised for manufacturing production.

Once the design is approved the manufacturing can be scheduled to produce the units. Gaining the approval for the building permits can be a time-costly event. "it is frustrating that every Dutch municipality has to evaluate our designs again. Sometimes we have just completed a unit in Utrecht and if we want to build the same unit in Amsterdam we have to wait several months before we again have approval, that is frustrating when you try to solve the housing crisis"[10]. The existing building code regulations delay the process of construction. Each municipality has to review modules on their compliance with the building codes. This delays the process significantly.

Once the manufacturing and groundworks have been completed, the transportation department of Daiwa Modular Europe transports the units to the project site. On-site, the units are assembled into a building in a matter of weeks. "Once the groundwork's are done the completion of the building can be completed in 5 to 6 weeks. Sometimes a table construction needs to be built for the architectural design, that usually takes the longest amount of time" [8]. The manufacturing of modules can take place at similar times to the groundworks. Once the groundworks are completed the benefits of assembling a circular building are significant.

Within Daiwa Modular Europe the circular business process is not aimed at the operation phase of their buildings. "Clients have all these systems in place to find tenants and users of the buildings, we do not take care of that" [8]. If necessary Daiwa Modular Europe provide maintenance services, however their clients usually have the maintenance of buildings organised internally. "Clients often have internal departments or long-lasting contracts with companies that provide these services" [8]. During the operation phase of a modular building, the asset managers are starting to realise that a modular building retains a certain amount of value. This requires a different approach to these modular buildings. "Modern asset managers of clients are realising that there is

[1] The statiegeld regeling is a Dutch deposit arrangement on soda & beer bottles, cans and crates. The arrangement incentives a centralised collection and reuse or recycling of these materials

[2] The MPG is a Dutch calculated number between 1 and 0 where the lower the number the better buildings perform. It stands for the Milieu(Environmental) Prestatie(Impact) of Gebouwen(Building).

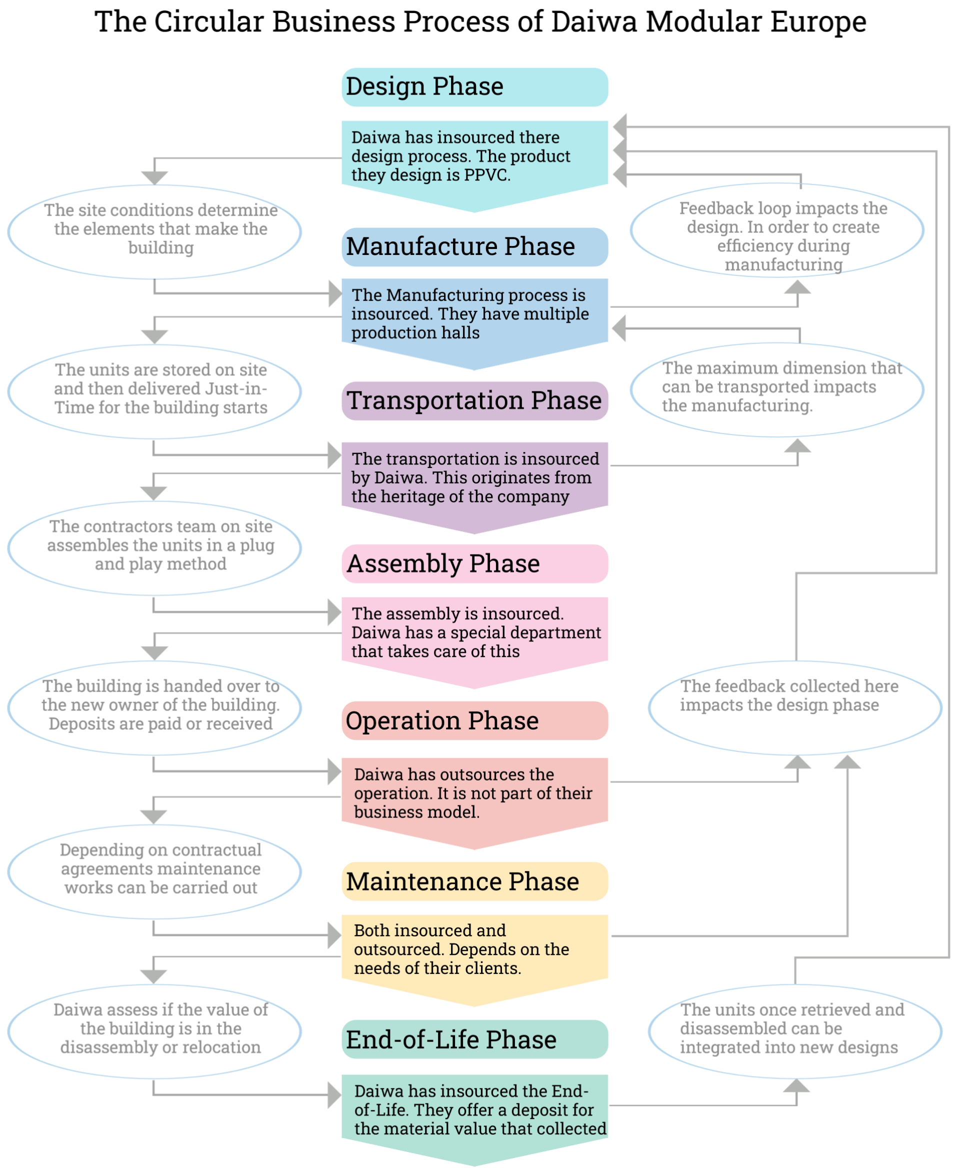


Figure 4.10: Circular/Modular Business Model for Daiwa Modular Europe(own work)

value in the modular ability and level of reversibility of their buildings" [9]. Daiwa Modular Europe experiences a difference in the market, as more asset managers realise that a circular building requires a different real estate management approach.

Due to the deposit arrangements and level of reversibility of a Daiwa Modular Europe building the End-of-Life phase is already beginning to be taken into consideration. Due to the housing shortage, there is not yet a need to remove buildings on building sites. " ... in the near future, the lease on a piece of land is going to expire, that would mean we would have to relocate a building of more than 800 units."[9]. This development has made Daiwa Modular Europe aware of the immense challenge that approaches them. "Within Daiwa, we will have an optimisation problem in the coming 2 years, [...] we cannot calculate these kinds of re-locations out of our heads without the use of proper computer programs" [8]. "Our Jan Snel departments make these kinds of relocation calculations often on a piece of paper because they have 5 to 20 units that need to be relocated. 800 units is a different challenge" [9]. Within Daiwa Modular Europe the understanding and need for proper relocation software tools has started to take shape, as they need to relocate an 800-unit building within 5 years.

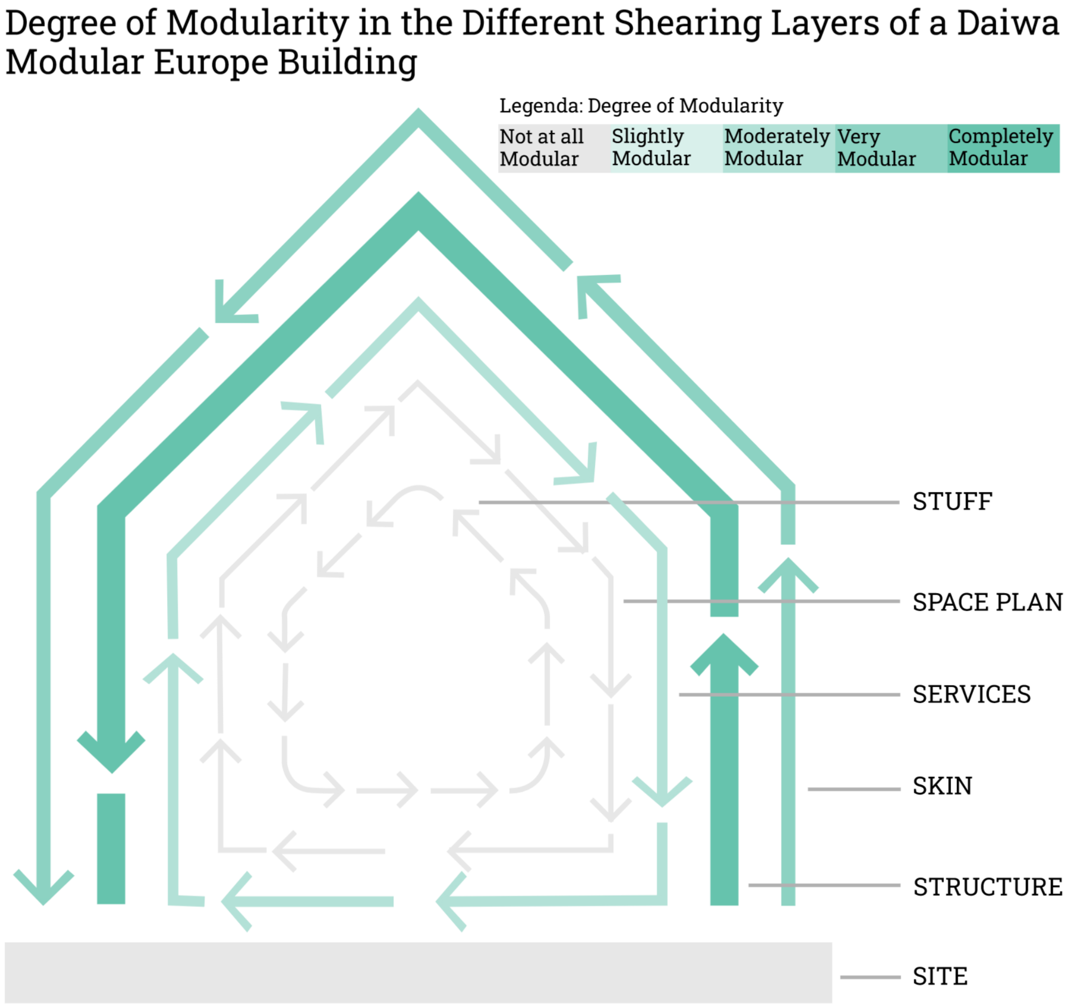


Figure 4.11: Degree of Modularity in the Different Shearing Layers of a Daiwa Modular Europe Building (Own work based on Duffy (1990))

4.2.3. Shearing Layers of Circularity

Due to the adaptability, timescale and expected durability of certain elements in buildings and subsequently the design, operation, maintenance and end-of-life strategies can be reviewed by using the shearing layers concept. This section contains an overview of the modularity of the different Shearing layers of modular building (Duffy, 1990). First, the *Site* layer will be briefly mentioned. Then the order in which the layers will be discussed and classified is *Structure*, *Skin*, *Service*, *Space Plan* and *Stuff*.

With the Daiwa Modular Europe building the *Site* layer is not reviewed as modular. This is because this layer is constructed through traditional construction and therefore is outside the scope of this research. That is why the layer is coloured grey in figure 4.11. The *Structure* layer of a Daiwa Modular Europe building is very modular. The structural components that support the cage structure and other units placed on top of these buildings can be disassembled. "You can just very easily unscrew every beam, it is screwed into the concrete foundations of the floor and the connecting corners." [9]. The only limiting factor in the design of these units is the concrete mix needed for the flooring. "We now still use *Caltrop*[3] shaped plastics in the concrete to reach the required strength, but we are developing methods of eliminating these and creating just flooring made out of only co^2 neutral concrete" [9]. Therefore the *Structure* layer is considered to be *Very Modular*.

[3]A **caltrop** (also known as **caltrap**, **galtrop**, **cheval trap**, **galthrap**, **galtrap**, **calthrop**, **jackrock** or **crow's foot**) is made up of two or more sharp nails or spines arranged in such a manner that one of them always points upward from a stable base (for example, a tetrahedron) (Merriam Webster, 2023)

The *Skin* layer of a Daiwa Building has some modular components. The finishing of the facade is usually completed on the project site through traditional methods."The facade is usually completed on the project site, purely out of aesthetic considerations." [9]. However, all other elements have already been placed. The windows and insulation materials have already been applied. "We can very easily disassemble the elements that are part of the isolation layer. Usually, it is a wooden frame made of screws, where the isolation material is placed in between." [8]. The *Skin* layer of a Daiwa Modular Europe building can thus be categorised as *Very Modular*.

The *Service* layer of a Daiwa building has a certain degree of modularity. The components that are part of the plumbing, HVAC and electrical systems need to be accessed easily. "Our clients have lots of experience in the rental sector, they find it important that these systems (HVAC, Plumbing and Electrical Fixtures) are accessible, even when tenants are not at home." [8]. The *Service* layer of Daiwa Modular Europe buildings can be described as *Moderately Modular*.

The layers *Space Plan* and *Stuff* did come up during the interviews. "We are not at all concerned about furniture or a finished floor. That is often the responsibility of the tenant or client. Since they do not want to see seams across the floors"[10]. There is a chance that these layers are modular, but within Daiwa Modular Europe there is no evidence for that. So these layers are classified as *Not at all Modular*.

4.3. Home.Earth

4.3.1. The story of Home.Earth

Home.Earth is a relatively new company, founded in 2021. Home.Earth has recognised that the Built Environment is a large polluter of greenhouse gasses and has made it its mission to combat this. "We have a clear ambition to construct our new homes with the lowest possible carbon footprint and to develop thriving and sustainable communities" (Home.Earth, 2023). Sustainable communities are an important part of their mission, they do not consider the income generated by the projects to be profit for the company (figures 4.12, 4.13). "(...) an important aspect is that we plan to give back 5% of the profits to tenants" [11]. The reward system for distributing profits among the tenants rewards the proper use of Home.Earth real estate.

The company has started to develop relations with several supply chain actors that can be capable of producing their buildings. They have started partnerships with the company Scandi Byg, within Denmark already recognised as one of the off-site producers. "(...) we have extensive experience in constructing environmentally friendly buildings, with previous projects achieving carbon footprints as low as five kilograms of co^2 equivalents per square meter per year. " (Home.Earth, 2023). In addition to the modular design approach, the operation phase is an equal part of the business process for Home.Earth. "(...) we place more emphasis on quality and durability in our construction investments. The operational phase plays a crucial role. We have an impact system that (...) informs and shapes our designs. " [12]. As builder and operator of the dwellings, the total costs of ownership can leave a significant mark on the commercial success of the company. Designing and building with this aspect in mind contributes to this process.

Home.Earth's method of modular design resides around the standardisation of core elements in dwellings regardless of the number of storeys. They have produced standardised elements for the staircases, elevators, and technical installations. "What we do is, we produce planar and volumetric elements. The volumetric designs consist of the core, staircase and elevator, and some smart hybrid designs that hold the technical systems for the bathroom, kitchen and HVAC. (...) and then we build and design the living room and bedroom made from planar elements around that. Since these do not need so much installation. Only some heating and electrics." [11]. The standardised elements of a Home.Earth building are produced volumetric or planar depending on the difficulty of the technical systems that are integrated into the components.

The Case for Industrialisation

An important factor for Home.Earth to make use of Industrialised Construction methods is resource efficiency. The time and material resources industrialisation saves is noted as one of the reasons. "With modular construction, we draw parallels with other industries where production has been optimized, such as the automotive industry, where standardization saves time and resources." [14]. Standardisation is then a method that can make it easier to implement a system across several different buildings. "(...) minimise the number of different types of materials. I think that one is also a big part of modular construction that you can improve the systems and the manufacturing of things that you use" [13]. The efficiencies in industrialisation then occur when these standardised elements can be constructed with similar construction materials. Thus reducing different amounts of resources.

4.3.2. The Circular Business Model

Within Home.Earth the decision to develop property is based on the entire lifetime of a building. The ability to lease the apartments to tenants and build a community is a deciding factor in the company. "Within Home.Earth we believe that housing is not only there for our profit, but the community should also benefit from a building that is well maintained." [13]. Residents of a Home.Earth building have the opportunity to receive financial compensation if the company Home.Earth realizes profits from the operation and maintenance phases. The decision to develop of course comes down to the business case of rental space, but building the community is just as important.

The design phase of a Home.Earth building has for a significant part already taken place. The development of standardised units that can connect through a plug-and-play type of detail allows them to make design configurations based on the limitations of the building plot. "The most important part for a developer is square meters that can be leased. When a plot is shaped like a rectangle most developers of modular houses can optimise a design based on the plot characteristics. However, when the plot has an awkward shape the traditional construction can usually optimise these better. We are trying to develop an adjustable system that also can cover these awk-

Figure 4.12: An illustration of the first Home.Earth project that they are constructing (Home.Earth, 2023)

Figure 4.13: An illustration of the first Home.Earth project that they are constructing(Home.Earth, 2023)

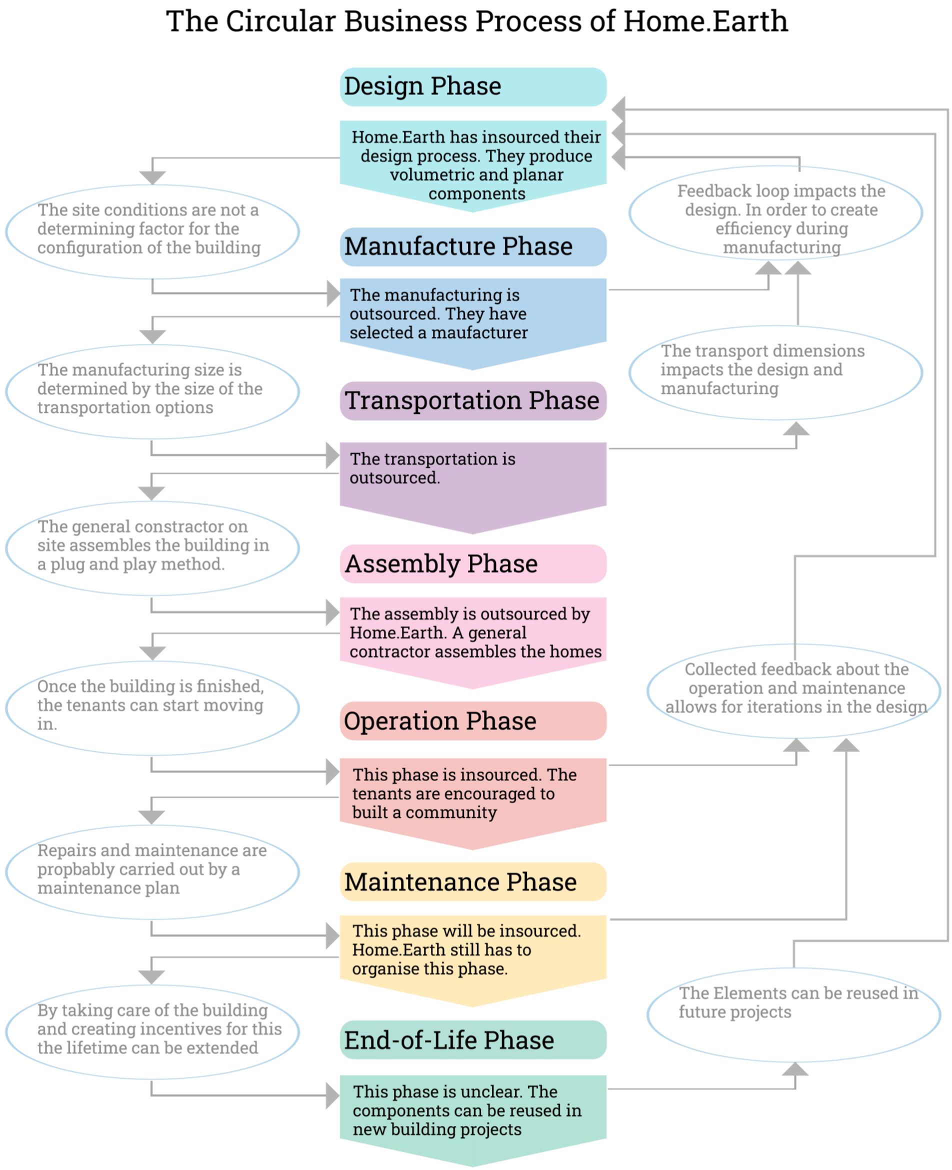


Figure 4.14: Circular/Modular Business Model for Home.Earth

ward plots." [11]. Home.Earth tries to implement a design system that allows for iterations to occur depending on site conditions while also manufacturing these elements off-site to optimise for a maximum of square meters.

The manufacturing of the planar and volumetric elements is executed by a Danish manufacturer with experience in prefabrication. Scandi Byg specialises in wooden module production for the Danish housing market. "Scandi Byg is the market leader in climate-friendly wooden construction" [14]. Home.Earth eventually aims to transition towards production facilities of their own. However, at this moment the production demand does not support the need for their facilities. "We are growing slowly, we are currently developing our first project" [11]. Home.Earth is still in the development phase of their first new building. Once several projects are being developed simultaneously Home.Earth can transition towards their facility.

The transportation and assembly on site are executed by Scandi Byg and a general contractor. Home.Earth is involved as an adviser and supervisor during this phase. "70% of our buildings volume is assembled" [13]. Since Home.Earth is such a relatively new company they do not have that much experience with these aspects of the construction so during interviews it remained difficult to discuss factors that influenced the construction of their buildings.

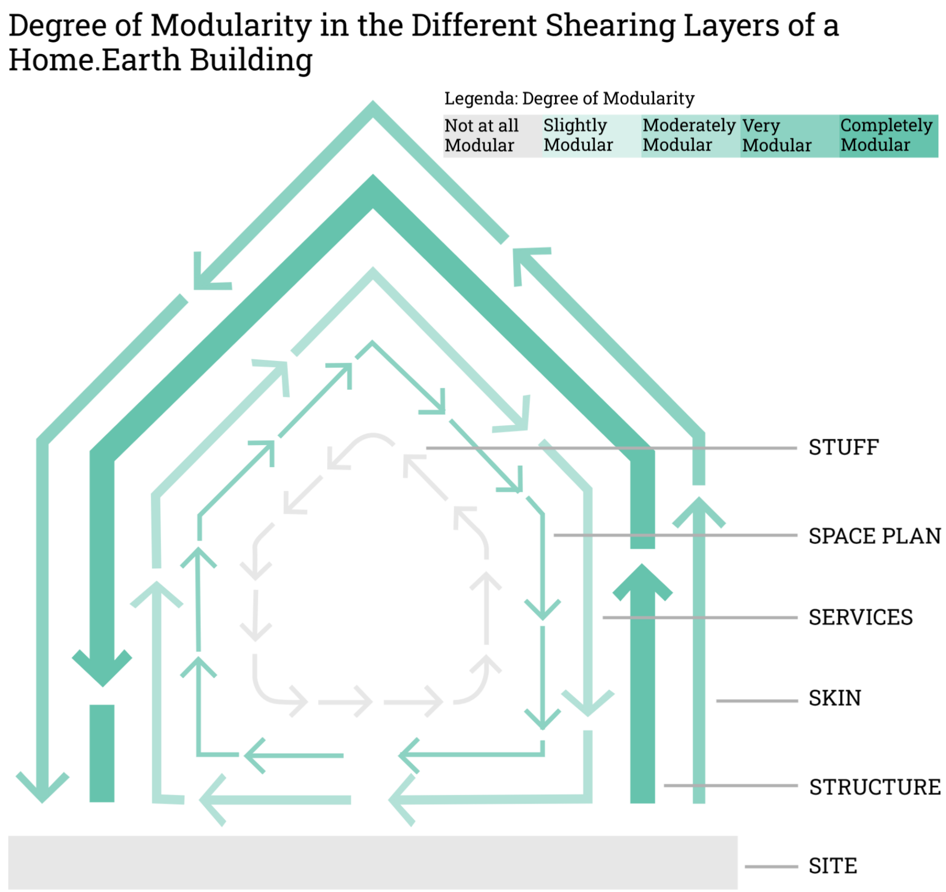


Figure 4.15: Degree of Modularity in the Different Shearing Layers of a Home.Earth Building (Own work based on Duffy (1990))

During the operation phase Home.Earth takes back control of the building. They find their tenants and aim to build a lasting relationship with their tenants. Since the tenants are a vital part of the sustainable communities Home.Earth aims to build within their buildings. "(...) of the reasons to remain owner after the completion is our desire to build communities" [11]. In efforts to give back to the communities and build lasting connections, a percentage of the profits is shared with the tenants. "We divide the profit and 10% goes to the investors and (...) 80% goes to cover all the expenses (...) and then 5% goes to the team. (...) 5% goes to the tenants."[11]. The business plan of Home.Earth distributes potential profits among internal actors of the projects. This is executed to promote a sense of community with employees and tenants.

The maintenance phase eventually impacts the business process of Home.Earth. In their designs, they have taken into consideration that maintenance works have to be performed in buildings. The accessibility of installations has been a relevant factor in the design of the modular elements. "We have realised that it is valuable to be able to execute repairs to installations when tenants are not home. Some of our industry partners have made us aware of this" [12]. In operating some small real estate projects, Home.Earth has realised that the accessibility of technical systems in the buildings when tenants are not home is a valuable design principle.

The End-of-Life phase of Home.Earth buildings is taken into consideration early on in the design process. The connecting details of all the planar and volumetric elements are designed with the disassembly and deconstruction in mind. "Let's say we have a wall and a floor, instead of using irreversible connections where you can basically not take them off. You have our mounting system that is reversible, where you can basically take it off again, (...) to a very detailed layer" [13]. The next challenge for Home.Earth lies in the reuse of designed elements. Elements that are designed and used now, need to be able to be reused 30 or 60 years later. "What we need to think of is how

Figure 4.16: An illustration of the first Home.Earth project that they are constructing (Home.Earth, 2023)

are we going to reuse those elements that we designed in version 1 that can be implemented again in version 5" [11]. The next step in the circular design process for a young company like Home.Earth is assuring that the iterations that are made to the volumetric and planar elements remain compatible with the existing designs.

4.3.3. Shearing Layers of Circularity

Due to the adaptability, timescale and expected durability of certain elements in buildings and subsequently the design, operation, maintenance and end-of-life strategies can be reviewed by using the shearing layers concept. This section contains an overview of the modularity of the different Shearing layers of modular buildings (Duffy, 1990). First, the *Site* layer will be briefly mentioned. Then the order in which the layers will be discussed and classified is *Structure*, *Skin*, *Service*, *Space Plan* and *Stuff*.

The *Site* layer of a Home.Earth building is, just as is the case for a CitizenM hotel and a Daiwa Modular Europe building, constructed through traditional construction. This is again shown in the figure 4.15 by the grey colour.

The *Structure* of a Home.Earth building consists of several modular elements. By the nature of the Home.Earth design the configuration of the different elements creates a modularity. "We design volumetric core components, like stairs, elevators and bathrooms, besides those we design planar elements that make the roofs, walls and floors of the living areas. (...) the local architects configure that into a building for a specific plot. " [11]. This means that the *Structure* layer can be classified as *Completely Modular*.

The *Skin* layer of a Home.Earth building can consist of several modular elements. The finishing on a facade or window placement can be different on each building plot. Designing planar elements that allow for this flexibility is necessary. "We always design in cooperation with local architects, because they are better at navigating through the different building codes and regulations that affect our facades." [12]). Based on this, the *Skin* layer of a Home.Earth building can be categorised as *Very Modular*(figure 4.16).

The *Service* layer of a Home.Earth building contains some modular elements. The design has gone through several iterations to improve the workflow of the maintenance and repair works. "Our initial designs placed the Cupboards inside the homes. Which made making appointments for repairs rather difficult. In newer iterations we placed them so that they are accessible in the hallway" [11]. Due to the volumetric modular components that encapsulate the bathroom, toilet and kitchen area. Elements designed by Home.Earth need a plug-and-play type of connection between several floors. That allows for some modularity. However, the modular replacement of these fixtures is difficult to assess. Therefore the *Service* layer can be considered *Moderately Modular*.

The *Space Plan* of a Home.Earth has some modular features. The planar elements that are designed as the walls, or partitions, can be configured based on the desired floor plan. The finishing floors are selected based on their durability. ”We have selected these floors in our buildings since these only have to be sanded every or so 10 years.” [11]. In addition Home.Earth has started conversations with the kitchenette suppliers that allow for refurbishment of the cabinets in a kitchen. ”We can imagine that tenants that live for 15 to 20 years in our building might want to change the aesthetic of the kitchen cabinets.” [13]. This means that the *Space Plan* layer of Home.Earth buildings can be considered *Very Modular*.

Equivalent to Daiwa Modular Europe, it is very difficult for Home.Earth to modularise the *Stuff* layer of their homes. This comes down to the tenants occupying the homes. Therefore this layer is classified as *Not at all Modular*. This does not mean the stuff in Home.Earth homes is not modular. There is simply no data available to support this.

5

Cross Case Analysis

This chapter outlines the commonalities and differences across the three case companies. The structure for this cross-case analysis will be as follows. First, a summary overview of the different approaches across the different phases of the circular business process will be provided. Then strategies across the different phases will be identified. Thirdly, the degree of circularity between the case company's buildings will be compared. Lastly, the different strategies identified across the different shearing layers will be discussed.

5.1. Summary of the Different Circular Business Process

As discussed in chapter 4 Case Study Results, the companies implement different strategies across the circular business process. Figure 5.1 highlights an overview of the different approaches to each strategy. The figure highlights whether the different companies insource or outsource certain activities in the process phase. The figure then describes the incentives for these companies to insource or outsource certain phases and how this affects their process.

All three case companies have a similar approach to the design phase of their buildings. The modular and core elements of their building designs are all insourced. They designed all technical connecting details, installations and systems. This allows the companies to then collaborate on designing a certain building plot with local architects. The architects bring knowledge about the local building codes and regulations. In collaboration with the local architects, they design the facade and configuration of different modules or elements.

In the manufacturing phase of the buildings, clear differences can be identified based on the business strategy of the case companies. CitizenM and Home.Earth have both outsourced there manufacturing. The incentive for this approach is that both companies do not produce the output desired to justify the decision of owning and operating a manufacturing facility. As a result CitizenM and Home.Earth both searched and reviewed several industry partners with which they can collaborate on a long-term basis to create feedback loops that can improve the manufacturing process. Opposite to the outsourced perspective of CitizenM and Home.Earth is the insourced perspective of Daiwa Modular Europe. Where CitizenM and Home.Earth decision was affected by the production output necessary to financially support a manufacturing facility. The decision for Daiwa Modular Europe to insource their manufacturing process rests on the revenue that can be gained by producing modules in their manufacturing facility.

The transportation phase relates to the manufacturing phase. There needs to be a steady supply of elements that need to be transported. Otherwise, the costs associated with the machinery necessary will negatively impact the company's financial results. Part of Daiwa Modular Europe expertise lies in the transportation of container elements. Transportation is therefore an element Daiwa Modular Europe has insourced. Home.Earth and CitizenM have outsourced this for the same reason as the manufacturing phase. The difference between Home.Earth and CitizenM at this phase lies in the scale of operation. As Home.Earth is active in the Danish housing market the transportation can mostly be executed

Summary of the circular business processes

Phases	Case companies: Citizen M	Daiwa Modular Europe	Home.Earth
Design	Insourced In cooperation with local architects. In order to comply to the existing building codes and regulations	Insourced In cooperation with local architects. In order to comply to the existing building codes and regulations	Insourced In cooperation with local architects. In order to comply to the existing building codes and regulations
Manufacture	Outsourced To selected factories in China. Selection is based on the ability to ship and transport the units.	Insourced Several facilities in the Netherlands and Germany produce and manufacture units in a assembly line system.	Outsourced A factory in Denmark is selected based on the several factors (close to the project site, experience with industrialised construction).
Transportation	Outsourced Global shipping companies transport the PPVC-units across the oceans. Local contractors take over the transport on land	Insourced From the storage location near the production facilities, the units are transported to the site	Outsourced The general contractor transports the units from the factory to the site.
Assembly	Outsourced The local contractor assembles the PPVC-units on the project site	Insourced Assembly of the units is organised by a dedicated team	Outsourced Local contractor assembles the elements on site under guidance of the Home.Earth
Operation	Insourced After completion of construction the operational department takes over.	Outsourced After completion of the construction, the owner of the building takes over the operation of the building.	Insourced After completion of construction the operational department takes over.
Maintenance	Insourced After completion of construction the maintenance department takes over. Organising repairs and other maintenance jobs.	Insourced and Outsourced After completion of the construction, maintenance services can be provided to the clients. Some clients have this organised already within their own organisation.	Insourced After completion of construction the maintenance department takes over. Organising repairs and other maintenance jobs.
End-of-Life	Unclear No clear exit strategy yet. The expectation is that the building is located on the location for a mimumum of 60 years.	Insourced Based on the negotiation phase, stipulations in the contract can arrange for the deposit of building elements	Unclear The connecting details are an important aspect of the assembly of the building. A clear strategy for the building over 60 years is unclear

Figure 5.1: Summary of the Different Phases of the Circular Business Process of the Case Companies, categorised based on whether these processes are in-sourced or outsourced

by one partner across one country. Due to the global scale of CitizenM, they are more reliable on a chain of transportation partners. A pitfall they have come across is the chance of structural deformation due to incorrectly levering the modules.

The incentives and enablers that exist for transportation, are also prevalent in the assembly phase. However, some nuances need to be addressed. The assembly of Home.Earth and CitizenM buildings is often executed by a general contractor with experience in modular/ Industrialised Construction. This results in another industry partner that needs to have the knowledge required. Whereas Daiwa Modular Europe has this phase insourced since they can maintain their production on a consistent level.

In the operation phase of their buildings Home.Earth and CitizenM share the same approach. Both companies have insourced this part of their circular business process. For CitizenM this makes since they are a hotel operator that also is a real-estate developer and owner. After the completion of construction Home.Earth acts as a landlord in regards to the buildings. Which means just as CitizenM they have insourced the operation phase. Daiwa Modular Europe on the other hand is not involved in the operation phase of buildings. "We are not interested in being landlords and dealing with tenants" [8].

Besides being operators of their buildings, Home.Earth and CitizenM have also insourced the maintenance of their buildings. The incentive for CitizenM to insource this activity is to make sure that repairs and maintenance works are executed as fast as possible. Since every day/night a room can not be booked, is a day/night that room costs money. Home.Earth decided to insource the maintenance so that they can collaborate with the tenants on this part, creating incentives for the tenants so they sustainably deal with their homes. Daiwa Modular Europe offers maintenance as a service to the company that becomes owner. However, most companies that become owners of a Daiwa Modular Europe building have extensive maintenance departments.

The End-of-Life phase of a Daiwa Modular Europe building is insourced by the company. They can, due to the level of reversibility, disassemble 75% of their building. Home.Earth and CitizenM have in some minor building levels a take-back arrangement with suppliers. This makes it hard to determine whether they have outsourced or insourced this part of the process. Additionally, within Home.Earth and CitizenM there is no independently provided data that makes statements about the level of reversibility of their buildings, although they claim or aim to reach between 60 to 80%.

5.2. Different strategies depending on the phase in the business process

Based on the different insource or outsource approaches to the circular business process phases the following strategies can identified. The identified strategies are discussed per circular business phase and presented in figure 5.2.

The first strategy for the design phase, Design Strategy 1 (DS 1), aims to prepare for the easiness of replacement. This strategy acknowledges that certain elements within a building need to be replaced before the end of its initial End-of-Life due to unexpected damages. These elements are usually part of a larger ensemble, but instead of replacing the ensemble the damaged element can be replaced. This reduces the produced waste to the damaged element(s).
DS 2 Procurement of Circular Suppliers, relates to the selection process of partners in the supply chain that enables a circular approach. Grasping that materials/components/elements/products that are added to a building at some point in time will be retrieved from a building is step 1 in this strategy. Step 2 is to select or collaborate with suppliers that offer a take-back service. This strategy complements DS1, but both can independently be applied.
DS 3 Modularize for Iterations, links to the modular design philosophy. This strategy assumes that improvements in materials/components/elements/products are continuously in development. As a result, the new iterations can be implemented when the End-of-Life of the materials/components/elements/products is reached. By acknowledging the possibility of implementing newer modules as part of the initial design the floor plan or other elements in the room/hall/building have to be replaced.
DS 4 Stand firm with your concept, rely on the design team to not adjust the dimension of the concept. It is tempting to adjust the concept so new iterations fit better. The design strategy is aimed at determining the dimensions during the concept development and then safeguarding these dimensions.
DS 5 Design for manufacturing, during the manufacturing process the most time can be saved. Designing with manufacturing in mind can result in fewer fixtures or other elements being integrated to reduce time on manufacturing.
DS 6 Configure to site specifics, the standardisation of elements/components allows for buildings to be assembled with the components that best fit the site conditions. Designing elements that can be configured to fit the existing building plot, requires the standardisation to be flexible.
DS 7 Integrating feedback, and designing feedback loops that influence the design process. The integration of feedback loops into the design phase can improve future iterations. Feedback acquired in the manufacturing, operation, maintenance or End-of-Life phase can certainly impact design iterations

The first strategy for the manufacturing phase, Manufacture Strategy 8 (MFS 8), aims to collect feedback about the manufacturing process. The collecting of feedback about the manufacturing process allows for iterations to introduce improvements.
MFS 9 Build collaborative partnerships, aims at developing and preserving collaborative partnerships with suppliers and designers. The collaborative partnerships allow for efforts that enable design iterations to take place with improved efforts for all involved parties.
MFS 10 Selection of a production method, impacts the company's decision to insource or outsource the manufacturing. The selection of a production method depends on the size of the operation. The decision to insource the manufacturing can only be supported if over several years a steady demand of components can be produced.

The strategy for the transportation phase, Transportation Strategy 11 (TS 11), aims to prevent structural deformation. The structural deformation of components during transportation can result in big cost overruns that affect the bottom line. Selecting partners that have experience with moving, lifting and transporting volumetric components can reduce the risks and thus the costs.

The strategy for the assembly phase, Assembly Strategy 12 (AS 12), revolves around Selecting knowledgeable partners. Just as is the case with the transportation phase, the Assembly phase can result in structural deformation if the parties involved have insufficient knowledge or experience with assembling volumetric components. Selecting partners that have experience or knowledge is beneficial and reduces risks and additional costs.

The (first) strategy for the operation phase, Operation Strategy 13 (OS 13), intends to Build sustainable relationships with clients. As the actual users of the buildings the development with users

Strategies developed based on the different phases of the circular business process

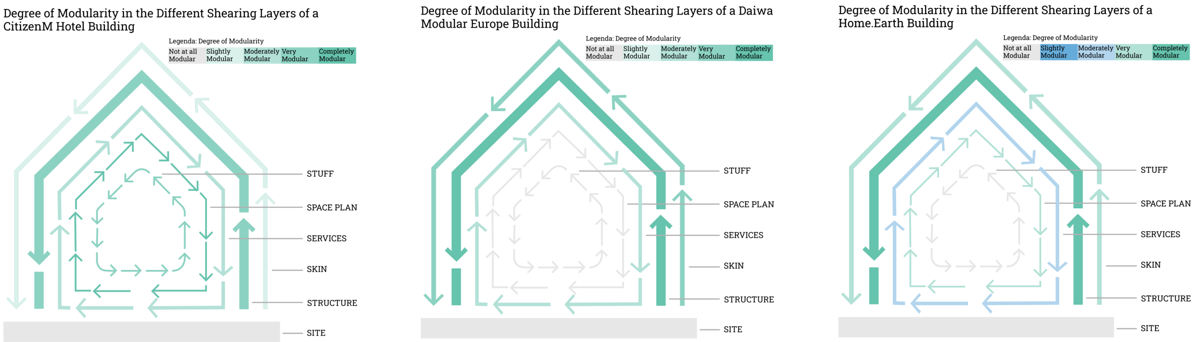
Phases			
Design	1	Prepare for replacement	Assumes that element need to be replaced before the expected End-of-Life. Allow for ease in replacement.
	2	Procurement of Circular Suppliers	Selecting partners or suppliers that enable a circular business process.
	3	Modularize for Iterations	Allow for iterations of elements to be combined with older or original modules.
	4	Stand firm with your concept	Do not adjust the dimensions that are determined in the concept. Differences in dimensions alter all aspects.
	5	Design for manufacturing	Reducing the amount of elements necessary in order to save time during construction
	6	Configure to site specifics	The standardised elements can de configured in order to fit a certain specific building plot. The design options are not limited by the site conditions
	7	Integrating feedback	Reviewing and actively searching for feedback from the other phases and incorporating this in the design phase
Manufacture	8	Collect feedback	Collecting feedback can provide valuable information that impacts the design and eventually can increase efficiency during manufacturing
	9	Build collaborative partnerships	Collaborative partnerships allows for efficiency improements that create benefits for all the parties involved.
	10	Selection of a production method	Insourcing or outsourcing the production can be supported if the expected output over several years support an own factory.
Transportation	11	Prevent structural deformation	Selecting knowledge partners that are aware of the risk in transportating volumetric components prevents damages and extra costs.
Assembly	12	Selecting knowledgeable partners	Selecting knowledge partners that are aware of the risk in assembling volumetric components prevents damages and extra costs.
Operation	13	Build sustainable relationships with clients	A long term relationship with users creates trust, a sense of ownership and results in proper use of the facilities provided
	14	Reward proper use of space	Delivering financial rewards to tenants when the costs of maintenance and operation are lower than expected or the profits are shared.
Maintenance	15	Prolong the lifetime of materials	Selecting materials that can have a extended life-time if they are properly maintained.
	16	Refurbish damaged or soiled materials	Procuring suppliers that offer a take-back/repair guarantee on the materials or components that are damaged or soiled
	17	Effortless maintenance works	Design elements and components that enables effortless maintenance works.
End-of-Life	18	Return materials to suppliers	Procuring suppliers that offer a take-back guarantee on the materials or components once these reach their End-of-Life
	19	Reimbursement arrangements	Forming contractual agreements that the building components represent a deposit value that is transfered at the End-of-Life of a building.

Figure 5.2: Identified strategies related to the different phases of the circular business process

in mind and working on a long time relation ensures proper and sustainable usage.
OS 14 Reward proper use of space, if the user takes care of the property adequately a reward for that behaviour can create incentives that continuously proper behaviour. However, it can also be the case that users or tenants make use of the building properly because of the reward. Either way, the proper use of the building reduces maintenance costs.

The first strategy for the maintenance phase, Maintenance Strategy (MTS 15), aspires to prolong the lifetime of materials. By proper maintenance of materials, the life-time of these materials can be extended. An important aspect of this is selecting materials that can be maintained easily and effectively.
MTS 16 Refurbishment of damaged or soiled materials, resolves around agreements with suppliers. These agreements should contain arrangements that ensure that products, components or elements are taken back when they are damaged, or soiled.
MTS 17 Effortless maintenance works, this strategy is aimed at enabling maintenance works to be effortless. Creating fast and effective work methods that are supported by design, so that replacements can be fitted quickly.

The first strategy for the End-of-Life Phase, End-of-Life Strategy 18 (EoLS 18), aims to return materials to suppliers. Comparable to the MTS 16, this strategy aims to close a material loop. When materials reach the End-of-Life they should be taken back by their suppliers.
EoLS 19 Reimbursement arrangements are agreements the manufacturer can make with clients about the residual value of the building at the End-of-Life phase. Similar to deposits on PET bottles for sodas, the building materials represent a value if they can be repurposed. The manufacturer and client make transactions at the start and end of projects that resemble a deposit on the building materials. These deposits can be additional costs above the costs for producing rentable square meters.



(a) CitizenM (b) Daiwa Modular Europe (c) Home.Earth

Figure 5.3: A comparison between the three case companies on a Degree of Modularity in the Different Shearing Layers of Buildings, categorised based on a scale of modularity ranging from "not at all Modular" to "Completely Modular"

5.3. Shearing Layers Concept

Reviewing and comparing the differences between the Shearing Layers of the buildings of the case company has been valuable in reviewing the interview data. Each company has implemented a certain degree of circularity in their buildings. However, in reviewing and sense-making of the data, a disparity between the answers became apparent. Each company's circularity efforts have started on a different shearing layer. As a result, the life-time associated with the components and layers varied. To coherently review and compare their intentions, the efforts need to be reviewed on the appropriate layer. This is where the Shearing Layer Concept has been valuable in reviewing the different case companies.

First, the differences of the Site layer will be discussed. Next, the disparities in the Structure layer will be reviewed. Thirdly, the difference in the Skin layer will be highlighted. Following that, the contrasts between the Service layers will be examined. Penultimately, the difference between the Space Plan layer will be discussed. Lastly, the differences between the stuff layers will be postulated.

Site

The activities that affect the site works are the groundworks. which consists of for instance utility connections, foundations and (semi) public green spaces. However, the site layer is by all companies still constructed through traditional construction. Therefore this layer lies beyond the scope of this research and a valuable comparison is not made.

Structure

The approach to the structure of the buildings differs between the three case companies. CitizenM makes use of steel container structures that as volumetric components can be disassembled from a building. Daiwa Modular Europe makes use of a steel and concrete cage construction that is screwed together during manufacturing. This allows them to disassemble the structure of their volumetric components. Home.Earth takes a different approach, they review the structure of their building as a combination of volumetric and planar elements that can be interlocked on the building site. This allows them to design their buildings more flexibly and in reaction to the local site conditions.

Based on the flexibility and reuse ability in other buildings Daiwa Modular Europe and Home.Earth have a higher degree of circularity. Whereas CitizenM can relocate their volumetric building components. However, the structural parts that make these components are more difficult to disassemble and reuse in other projects.

Skin

The approach to the skin layer is in the design phase similar between the three case companies. All companies collaborate with local architects. This collaboration is a result of the knowledge local architects have over the building regulations that apply to specific building plots. In their circularity efforts, all companies make use of a finishing facade that is assembled on-site to the existing structure. Aesthetics are the underlying argument here.

CitizenM constructs the skin of their buildings with a combination of traditional construction and Industrialised Construction. The facade for the hotel rooms is often manufactured and assembled on-site. Whereas the facade of the lobby and foyer are often constructed through traditional construction. This results in CitizenM being classified as slightly modular in comparison to the very modular of Daiwa Modular Europe and Home.Earth on

The Degree of Modularity in the Different Shearing Layers of Buildings

	Case companies		
Layer	Citizen M	Daiwa Modular Europe	Home.Earth
Site	Not at all Modular -	Not at all Modular -	Not at all Modular -
Structure	Very Modular The structure of CitizenM buildings consist of volumetric steel cages that can be interlocked and unlocked on site and moved to a different location	Completely Modular The structure of Daiwa houses consists of steel and concrete cages can be interlocked and unlocked on site and can be disassembled in the factory.	Completely Modular The wooden planar elements can be interlocked and unlocked on the building site.
Skin	Slightly Modular The skin or finish of the hotels is often completed by means of traditional construction. This Skin is clicked onto the existing facades	Very Modular The finishing skin of the building can be integrated in the factory. But mostly is clicked into place at the project site for aesthetic reasons.	Very Modular The finishing skin is a combination of pre-fabricated elements that can interlock with the existing planar elements.
Services	Very Modular The service layer is accessed relatively easy. The replacement rate of items is taken in condiseration when covering elements are designed.	Moderately Modular The service layer is accesable when tenants are not at home. The replacement rate of items is taken in condiseration when covering elements are designed.	Moderately Modular The service layer is accesable when tenants are not at home. The replacement rate of items is taken in condiseration when covering elements are designed.
Space Plan	Completely Modular The flooring system can be replaced on a piece by piece method. The supplier of these elements than takes the floorings systems back to reuse these in their supply chain	Not at all Modular This layer is not taken in consideration. This layer is often the responibility of the tenant	Very Modular The flooring systems are chosen based on the lifetime and maintenance required. This is casued by the legal requirements of the Danish building code and the partly because of the conviction that this is the most modular approach
Stuff	Very Modular The furniture supplier offers the possibility of refurbishing their products. It is contractually agreed that they take back their products	Not at all Modular This is not taken in consideration	Not at all Modular This is not taken in consideration

Figure 5.4: The Degree of Modularity in the Different Shearing Layers of Buildings, categorised based on a scale of modularity ranging from "not at all Modular" to "Completely Modular"

the circularity of their buildings' skin layer.

Services

The methods applied to the service layer of each building are comparable across the three case companies. All companies prioritise the accessibility of utility services in their building. Based on the presumption that the maintenance of these appliances becomes significantly easier. As a result, all three companies are classified similarly on their degree of circularity.

Space Plan

On the layer Space Plan the differences between the different companies become more apparent. CitizenM has their circularity efforts developed the furthest on this layer. An important aspect of their circularity efforts relates to contractual agreements with suppliers about take-back guarantees when products are damaged, soiled or at the end of their lifetime.

Home.Earth implements a different approach to the circularity efforts on the Space Plan layer. They have made efforts to prolong the lifetime of components on this layer. Selecting materials for their durability and ease of maintenance. Additionally, creating financial incentives for tenants to properly use the building.

Daiwa Modular Europe has mostly ignored this layer and the components that are associated with this layer. They consider this layer not part of their responsibility. As a result, their efforts on this layer can be ignored.

Stuff
On this layer, only 1 of the three case companies makes active efforts to circularise the layers. The efforts of Home.Earth and Daiwa Modular Europe are therefore ignored or deemed irrelevant. CitizenM strategy for circularising the stuff layer comes down to two methods. First, the procurement method of suppliers. They are selected based on their possibility to comply with Environmental Sustainability Goals that are developed within the company.
Secondly, similar to the Space Plan strategy CitizenM makes arrangements with their suppliers for take-back guarantees. Especially with the suppliers of their furniture, these arrangements are made. This is mostly caused by the mess some guests can make of the furniture. In stead of replacing the entire furniture piece damaged or soiled parts are replaced. Or the entire chair is refurbished.

6

Strategy Development Framework

6.1. Need for the Framework

During the process of reviewing the existing strategies that are implemented across the case companies the dawning realisation that a clear and concise overview of existing strategies is missing. To present the collected strategies this framework is developed. The framework is based on the data collected from the three case companies, this means that strategies implemented by other companies may not be represented here. However, this does not mean that those other strategies can not result in well-maintained circular buildings that are constructed through Industrialised Construction.

The framework can benefit Circular Building by transitioning towards a Industrialised Construction approach. The Circular Building practice has slowly started to be implemented in the Built Environment. Yet, efforts for circularising new buildings are slowly implemented. Circularising the entire building requires a lot of effort. Companies that aim to circularise their new building projects can benefit from some of the methods of the Circular Industrialised Construction framework. By applying the Circular Industrialised Construction framework companies are offered strategies that allow them to transition towards a standardised circular approach.

Even companies that are already actively implementing circularity efforts into their Industrialised Construction process acknowledge the immense task ahead. To make these changes manageable, this framework is developed. For companies to implement Industrialised Construction or Circular Economy this framework offers an overview of the existing strategies for accomplishing this. Application of this framework, even with incremental results, is encouraged. Since it allows for a transition towards a more circularised or industrialised Architecture, Engineering, Construction and Operation sector.

During the data collection, it became apparent that even within companies there exist multiple strategies that enable a circular building. Some of these strategies are partly executed on some components that are part of a Shearing Layer. While other components that are part of the same layer are not circularised. This is partly due to the implied simplicity of the Shearing Layers Concept, and partly due to the difficulty of circularising an entire building or layer in one.

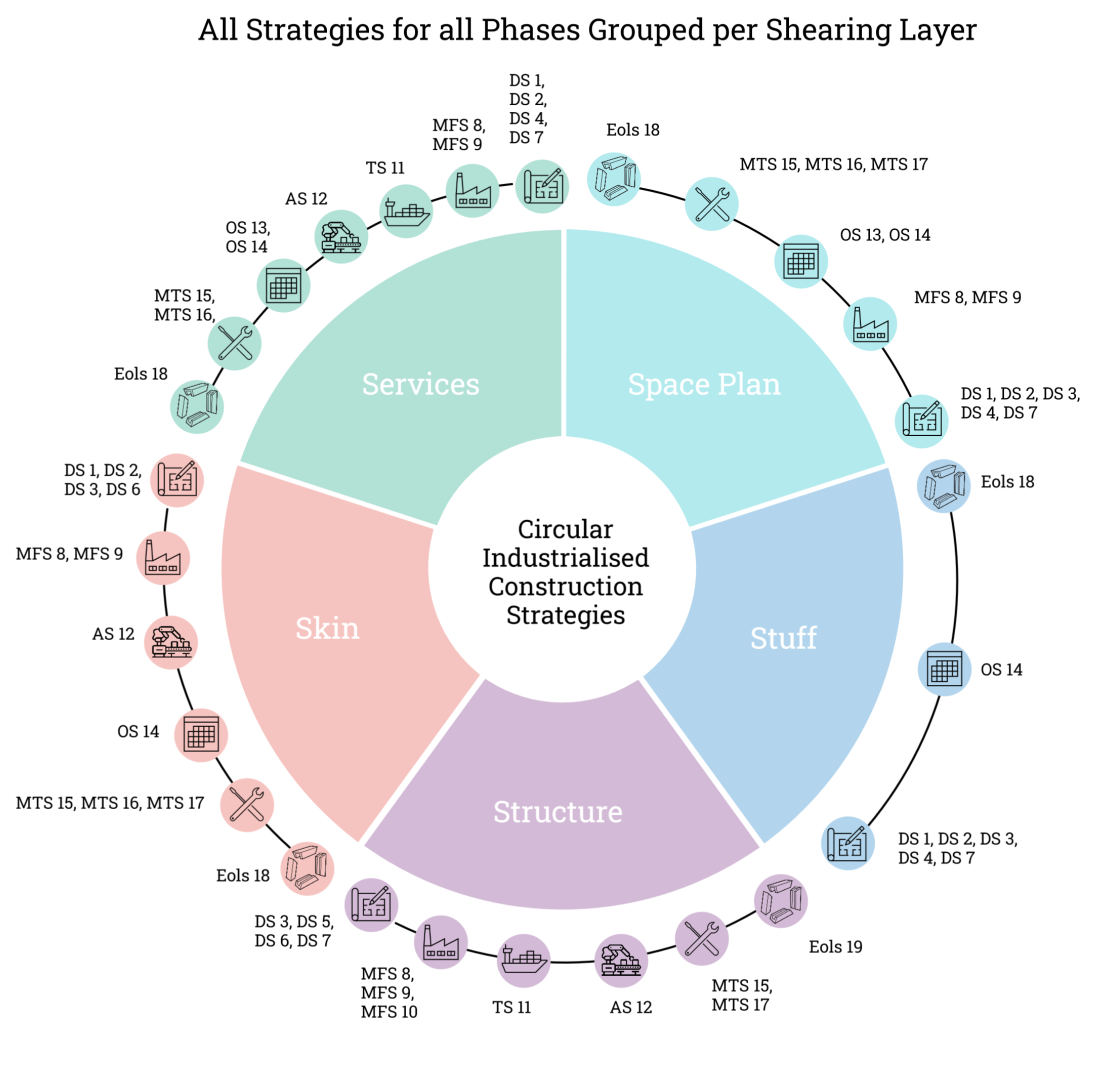
In essence, this framework presents an overview of all the identified strategies categorised on the different shearing layers (Y-Axis) in which they are applicable. The strategies are then grouped based on the phases in the circular business process (X-Axis) (Figure: 6.1.)

6.2. The Framework in Practice

The framework categorises each Shearing Layer separately. In each layer, the identified strategies from the different Circular Business Phases as discussed in Chapter 4 and 5 will be highlighted. Additionally, strategies that strengthen each other will be addressed explicitly. Along with the figure 5.2 the framework offers a directory for companies reviewing their possibilities.

6.2.1. Site

The Site layer of a building has barely been reviewed during this research. Mostly because the case companies often used traditional construction in this layer. As a result no strategies for Cir-



DS	1	Design Strategy	1	:	Prepare for replacement
DS	2	Design Strategy	2	:	Procument of Circular Suppliers
DS	3	Design Strategy	3	:	Modularise for iterations
DS	4	Design Strategy	4	:	Stand firm with your concept
DS	5	Design Strategy	5	:	Design for Manufacture
DS	6	Design Strategy	6	:	Configure to site specifics
DS	7	Design Strategy	7	:	Integrating feedback
MFS	8	Manufacture Strategy	8	:	Collect feedback
MFS	9	Manufacture Strategy	9	:	Build collaborative partnerships
MFS	10	Manufacture Strategy	10	:	Selection of a production method
TS	11	Transportation Strategy	11	:	Prevent structural deformation
AS	12	Assembly Strategy	12	:	Selecting knowledgeable partners
OS	13	Operation Strategy	13	:	Build sustainable relationships with clients
OS	14	Operation Strategy	14	:	Reward proper use of space
MTS	15	Maintenance Strategy	15	:	Prolong the lifetime of materials
MTS	16	Maintenance Strategy	16	:	Refurbish damaged or soiled materials
MTS	17	Maintenance Strategy	17	:	Effortless maintenance works
EoLS	18	End-of-Life Strategy	18	:	Return materials to suppliers
EoLS	19	End-of-Life Strategy	19	:	Reimburment arrangements

Figure 6.1: Circular/Modular Business Model for Home.Earth

cular Industrialised Construction were identified that impact the Site layer.

6.2.2. Structure

The structure layer(figure 6.2) of a building can be impacted by the following strategies; Design Strategies 3, 5, 6 & 7, Manufacturing Strategies 8, 9 & 10, Transportation Strategy 11, Assembly Strategy 12, Maintenance Strategies 15 & 17 and End-of-Life Strategy 19.

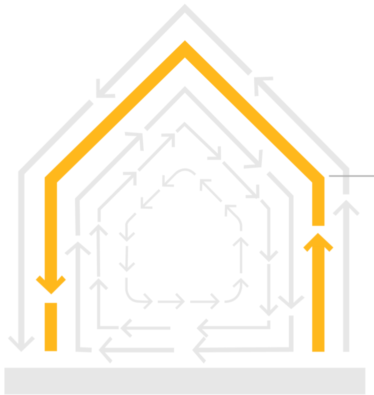


Figure 6.2: The layer Structure of the Shearing Layer concept diverted to the Circular Industrialised Construction Framework

The combination of Design Strategies 3, 5 & 6 can create an impact on the circularity and modularity of standardised elements. The combination offers much flexibility to the design of a building. Due to the expected long lifetime of this layer, the other impact-full strategy is End-of-Life Strategy 19. This method allows companies to organise their business venture based on the presumption that the component or elements retain their value. Thus creating a loop where used elements can be integrated back into the design phase and reduce the material costs for new products.
Besides the Design strategies and the End-of-Life strategies, two other strategies impact the *Structure* layer. Those are Transport Strategy 11 and Assembly Strategy 12. Implementing these methods can reduce potential costs and delays due to structural deformation during the transportation or assembly of components.
The remaining methods are Manufacturing Strategies 8, 9 & 10 and Maintenance Strategies 15 & MTS 17. these are all enabling strategies that improve the efficiency of elements associated with this layer. Or they aim to prolong the lifetime of the components.

6.2.3. Skin

The *Skin* layer of a building can be impacted by the following strategies; Design Strategies 1, 2, 3 & 6, Manufacturing Strategies 8 & 9, Assembly Strategy 12, Operation Strategy 14, Maintenance Strategy 15, 16 & 17 and End-of-Life Strategy 18.

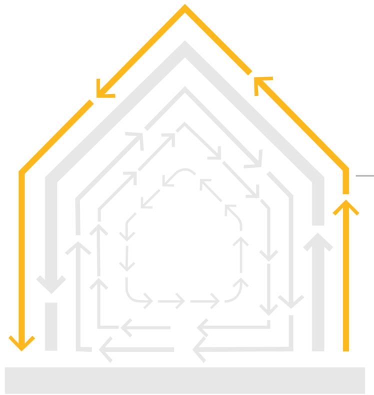


Figure 6.3: The layer Skin of the Shearing Layer concept diverted to the Circular Industrialised Construction Framework

A combination of strategies Design Strategies 1, 2, 3 and 6 impacts the layer *Skin* significantly. Due to the shorter expected life span of this layer, the possibility of iteration or replacements to be installed needs to be taken into consideration. This means that this layer replaces materials at the end of their lifetime with other materials. Organising the expected replacement and selecting & co-operating with suppliers that provide services for this replacement is necessary. The Maintenance Strategy 16 and End-of-Life Strategy 18 complement the design strategies in this aspect.
Just as with the layer *Structure* the strategies Manufacturing Strategies 8 and 9 increase the efficiency during production. The assembly of the *Skin* layer needs to happen carefully since the element can still suffer from structural deformation. This is where Assembly Strategy 12 fits in.
Strategies Operation Strategy 14 and Maintenance Strategy 15 revolve around the aim of increasing the expected lifetime of the materials. When the layer is properly maintained the expected lifetime can be prolonged. Thus reducing the need for replacement and other materials to be used. Maintenance Strategy 17 aims to improve the efficiency of maintenance of the *Skin* layer. If the maintenance of the layer is executed efficiently, the costs associated with this layer or the maintenance works can also be reduced.

6.2.4. Services

The *Service* layer of a building can be impacted by the following strategies; Design Strategies 1, 2, 4 & 7, Manufacturing Strategies 8 & 9, Transportation Strategy 11, Assembly Strategy 12, Operation Strategies 13 & 14, Maintenance Strategies

15, 16 & 17 and End-of-Life Strategy 18.

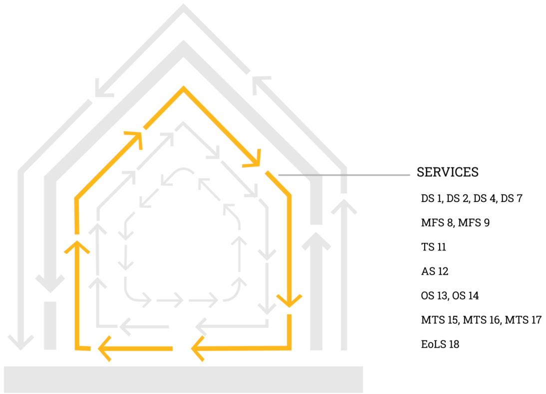


Figure 6.4: The layer Services of the Shearing Layer concept diverted to the Circular Industrialised Construction Framework

The combination of strategies Design Strategies 1, 2, 4 & 7 influences this layer. The expected lifetime of components in this layer results in replacements while the structure is expected to remain standing. As a result, the replacement of these service components needs to be considered or prepared for during the design. Selecting suppliers that acknowledge the replacement rate and supplement this procedure by providing services for this can increase the circularity efforts. Integrating feedback about the manufacturing, operation and maintenance impact of this layer creates efficiencies.
Strategies Manufacturing Strategy 8 & 9 aim to create substantial efficiencies in the manufacturing of components for this layer. The risks of structural deformation can be mitigated by implementing strategies Transportation Strategy 11 and Assembly Strategy 12.
Methods Operation Strategy 13 & 14 and Maintenance Strategies 15 & 17 are aimed at prolonging the lifetime of the components. First, by creating incentives for proper usage. Secondly by adequately maintaining the selected materials.
Procedures Maintenance Strategy 16 and End-of-Life Strategy 18 both benefit from arrangements made with strategy Design Strategies 2. The take-back guarantees that are arranged with the suppliers can be executed. Instead of these products being reduced to waste, they can be garnered by their manufacturers.

6.2.5. Space Plan

The *Space Plan* layer of a building can be impacted by the following strategies; Design Strategies 1, 2, 4 & 7, Manufacturing Strategies 8 & 9, Operation Strategies 13 & 14, Maintenance Strategies 15, 16 & 17 and End-of-Life Strategy 18.

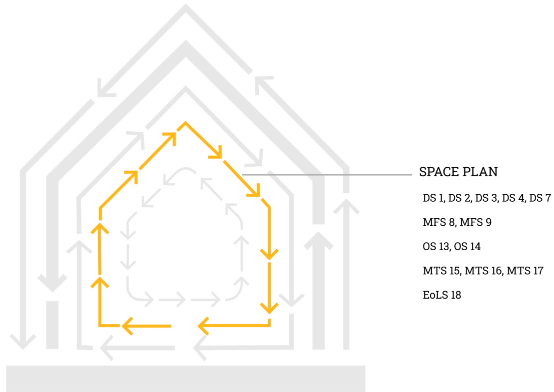


Figure 6.5: The layer Space Plan of the Shearing Layer concept diverted to the Circular Industrialised Construction Framework

A combination of strategies Design Strategy 1, 2, 4 & 7 have the most significance on the *Space Plan* layer. This layer is impacted by a short expected lifespan. Changes or replacements are almost synonymous with this layer. Designing and enabling these replacements can be beneficial for the circularity efforts in this layer. Incorporating feedback enables newer versions to be implemented effectively.
Creating noteworthy efficiencies in the manufacturing of components for this layer is the primary goal of Manufacturing Strategies 8 & 9.
Strategies Operation Strategies 13 & 14, and Maintenance Strategies 15 & 17 are geared towards prolonging the lifespan of components, primarily through the establishment of incentives for proper usage and the effective maintenance of selected materials.
Both Maintenance Strategy 16 and End-of-Life Strategy 18 derive advantages from agreements facilitated by Design Strategy 2. The take-back guarantees negotiated with suppliers can be implemented, ensuring that instead of becoming waste, these products can be reclaimed by their manufacturers.

6.2.6. Stuff

The structure layer of a building can be impacted by the following strategies; Design Strategies 1, 2, 3, 4 & 7, Operating Strategy 14 and End-of-Life Strategy 18.

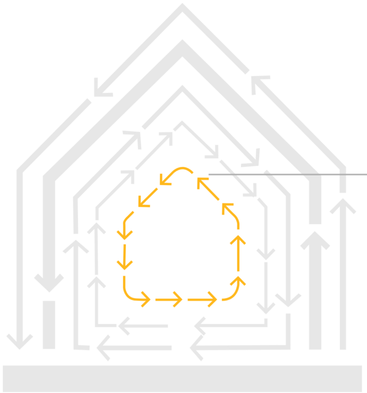


Figure 6.6: The layer Stuff of the Shearing Layer concept diverted to the Circular Industrialised Construction Framework

Combining Design Strategies 1, 2, 3, 4 & 7 creates a substantial impact on the *Stuff* layer of a building. This layer is difficult to implement due to that these components are often owned by tenants or users. However, for the few organisations that own products in the stuff layer, the combination of the design strategies is deemed beneficial. Designing for replacements and iterations and standing by these choices is difficult but it allows suppliers to adjust and to start creating incremental improvements in the circular efforts of the products.

Rewarding users by properly using these elements increases the expected lifetime of these materials. Arrangements made with strategy Design Strategy 2 benefits End-of-Life Strategy 18. The execution of take-back guarantees with suppliers ensures that these products, rather than ending up as waste, can be reclaimed by their manufacturers.

7
Discussion

This chapter contains the discussion. In the discussion, the findings and their relation with existing theory and literature will be reviewed. First, the Role of Industrialised Construction within the case companies will be discussed (Section 7.1). Next, in section 7.2 the Circular Business Process will be examined. Thirdly, the Shearing Layers Concept will be reviewed (section 7.3). Penultimately, the Circular Industrialised Construction Framework will be discussed (section 7.4). Lastly, in section 7.5 the limitations regarding the research will be reviewed.

7.1. The Role of Industrialised Construction within the case companies

First, the argument for implementing standardisation efforts is within the literature based on efforts to improve resource efficiency. Several resources are identified where efficiencies can be gained. The resources where this efficiency can be achieved are Cost, Material, Time, Quality and Safety.

The benefits to the cost-effectiveness of standardisation in the manufacturing process relate to a reduction in materials and time required for the production (GIBB & ISACK, 2001; O'Connor et al., 2015). During the interviews, the effects of standardisation on the costs of a building were discussed. But most notable, was that this was not an incentive for the development of standardised components, elements or modules. Several interviewees noted that the costs are similar to traditional construction.

The material resource efficiency in the process of standardisation is the assumption that due to prefabrication the required resources can be more effectively procured. Thus only the necessary materials are procured (Ajayi et al., 2017). Two of the three companies did not consider this for the application of standardisation. This is most likely because they outsourced the manufacturing. The third company, which insourced the manufacturing, noted that their efficiency in regards to resources comes down to economy of scale benefits. They could more effectively procure the materials since they could be ordered in large quantities.

The efficiency in the process of standardisation for the resource time should result in less time spent during construction. The time efficiency is created by executing works in parallel with each other (Tsz Wai et al., 2023). Two of the three companies argued that time efficiencies in the construction process are the most important incentive for developing standardisation. The efficiencies gained in the timeline of their projects have consequently impacted the costs of a project. However, they did not see the improvements in time as a reduction in costs, but an increase in the possibility to generate revenue quicker. The third company has yet to start the assembly of its first building.

The quality efficiencies in the standardisation process can be attributed to the creation of constant climate conditions. The repetition allows the production to produce an increase in quality due to familiarity with the proceedings. One company cited that the quality that can be achieved by standardisation was a significant incentive in choosing Industrialised Construction. A reason for this might be that this company has buildings in their portfolio that are constructed by traditional construction and Industrialised Construction. One interviewee noted that the difference in quality is significant. The significance was attributed to the fact that workers learned the method that pro-

duced the best quality way quickly. The two other companies did not mention the supposed quality improvement.
The final resource, Safety, has the potential to yield efficiencies through the standardisation process. Moving activities that require heavy machinery to a factory setting can create awareness about potential hazards when working near them. Additionally, improvements in the mental health of construction workers can be attributed to a Industrialised Construction work environment. Efficiencies in the safety resources were not discussed. However, one company mentioned that they think it is valuable that most of their employees originate from close vicinity. Thus, allowing employees to arrive to work by bike or public transport.

Secondly, the different approaches implemented by the case companies to standardise the production process. Lawson et al. (2014) describe several classifications that can be implemented in the Industrialised Construction approach. Those classifications are **Components**, **Elemental** or **planar systems**, **Volumetric systems** and **complete building systems**. A combination of several classifications can be used to construct a building. Two of the three companies mainly use a combination of traditional construction (ground works) and complete building systems that are delivered mostly finished on site. Both companies deliver these when the site serves the solution. The dimensions of the units are predetermined and hard to adjust to site-specific conditions. However, the third company has developed a combination of traditional construction (ground works), planar systems, volumetric systems and complete building systems. This allows them to configure their approach. Thus the solution serves the site.

7.2. Circular Business Process

The design phase lies at the start of circularity, where thoughtful decisions echo through the lifecycle of buildings (van Stijn et al., 2021). The Ellen MacArthur Foundation's butterfly diagram represents that if we want to close the material loop then the technical (design) loop needs to find solutions. The three case companies support this approach to the design phase. Although, they all make different types of real estate they remain in charge of their design process. The ability to be in charge of the design process effectively impacts approaches to the operation, maintenance and End-of-Life phase of buildings. One of the interviewees mentioned that the fact that coworkers from another department are impacted by his decisions influences his decisions. In other words, if he makes a decision that results in more work for his coworker then he will reconsider. Two of the three case companies stated, that being in charge of the design phase makes the process simpler. The Circular Industrialised Construction design process requires knowledge about standardisation and being able to do that across the entire product line results in an uncomplicated manufacturing process.

To implement and create a common understanding among designers several design philosophies have been developed. These design approaches can range from Design for Disassembly, Design for Deconstruction, Design for Disassembly and Deconstruction and Design from Disassembly (Charef et al., 2022). All three case companies acknowledge that considering these design philosophies enables them to construct their building. The approach of Design for Disassembly was considered in nearly all case companies' approaches. This approach enables the designers to think about the building as a collection of different modules. One case company is aware of the fact that future buildings need to be able to incorporate previous design iteration in the building products. In this sense, they are aware of the Design from the Disassembly approach. However, whether this approach is feasible for this company remains to be seen. In another case, the company has implemented the Design for Disassembly approach for interesting incentives. Due to the line of business in which they operate, some modules of products can be damaged, wrecked or soiled beyond repair. This has resulted in the realisation that modules need to be replaced quickly and efficiently. This results in using the Design for Disassembly philosophy for a Design for Ease in Replacement approach.

Being in charge of the design process is an enabler in applying the circular design process. The control over the design process is also attributed as an enabler for Industrialised Construction. Combining Circular Building and Industrialised Construction can effectively be combined in the design phase of a construction process(Anastasiades et al., 2021; O'Connor et al., 2014). The three case companies reflect this, all three are in charge of the design process, and that enables the Circular Industrialised Construction approach. Besides the design phase, the feedback from the manufacturing, assembly and maintenance of the Circular Buildings results in valuable knowledge. The knowledge obtained through the manufacturing and maintenance process leads to incremental, yet crucial, changes in the design. These changes in the design are implemented to increase efficiency and soothe the phases after design completion. The two case companies that outsource their manufacturing process expressed that a collaborative relationship with the manufacturer enables them to improve the circular and standardised aspects of the building.

The aspect of ownership over the building has been identified as an enabler in the circular business process. This is often represented by integrated contract and procurement procedures, such as DBFMORE (Straub et al., 2012). Two of the three case companies conveyed that the ownership of a building as Owner/Developer has incentivised them to consider the material and technical loops in their building. As previously noted, the feedback loops within one of the companies drive decision-making that aligns with long-term benefits.
However, the third case company expressed several times that they are not interested in the ownership of their building. Moreover, they solely operate as a developer. Nevertheless, they can construct buildings that have the potential to be disassembled. They mentioned that an important enabler in creating volumetric units that can be disassembled is deposit arrangements with the owners. They offer the owners of buildings the possibility to disassemble or relocate the units that are part of the building.

7.3. Shearing Layers Concept

The Shearing Layers Concept has been identified as an effective method to visualise the different components that comprise a building (Pushkar, 2015). Due to its plainness, the concept has been widely used and adopted for several other purposes. The plainness enabled this research to effectively visualise on which layer the circular efforts of the case companies took place.

The Shearing Layers Concept proved to be an effective method for comparing the different circular business approaches. Since the companies all aim to integrate circularity in their building it turned out to be valuable to realise which layer/component they were discussing. Since the different components the case companies are trying to circularise, the different lifetimes of these components became increasingly relevant. A limitation of this approach was that there are still several components that are part of a layer. No company has been able to circularise all the layers of a building, except for the *Structural* layer. The different levels of circularity between the components of a layer impede the classification of these layers. As a result, the components that remain to be circularised were not taken into consideration. However, the decision to use this framework, compare the case companies and classify their circularity efforts needs based on the framework still resulted in valuable insights. To clarify, the decision to use to Shearing Layers Concept despite the limitations was influenced because the framework allows for an effective comparison between the different lifetimes of components in 1 building.

Another limitation of the Shearing Layer Concept is the fact that it was developed for permanent and traditional construction. For instance, the concept assumes that the structural layers are constructed by concrete and steel beams & columns. Building technology has advanced significantly since the first introduction of the Shearing Layers Concept. An example of this is the modular building. Due to the ability to be moved and relocated the connection with the *Site* layer becomes difficult to imagine. As a result, the lifetime associated with some components does not perfectly relate to the lifetime displayed in the Shearing Layer Concept.

Additionally, the Shearing layer concept assumes that the *Skin* layer of a building contains all the insulation, windows and weather proving. With modular building components the *Skin* layer is often reduced to the finishing elements of the facade. These facade elements are rarely integrated into the prefabrication process due to aesthetics.

7.4. Circular Industrialised Construction Framework

Çimen (2021) endorses the overall response of the construction sector. The sector is reluctant and slow in the transition. Many companies have started with a different approach to circularity. The framework aims to combine all these different strategies. A combination can act as a directory, where all the possible strategies can be combined.

The Circular Industrialised Construction framework is developed to categorise the identified strategies that are applied by the case compa-

nies. A prospect of the framework is that depending on the different layers the strategies that can be applied are classified. The framework groups the different strategies per layer and illustrates the different circular business phases in which the strategy can be applied.
In designing the framework the aim was to create a coherent and rigid framework that could be implemented in the industry. Due to the substantial amount of strategies the framework has introduced a degree of ambiguity. This ambiguity is mostly caused by the fact that multiple strategies can or sometimes need to be applied to execute a strategy effectively. This limits the effectiveness of the framework, considering a lot of nuances that need to be taken into consideration.
With all the different layers that are part of the framework, it is hard to produce an appealing overview of all the strategies in 1 figure. So the different strategies in the different layers have been abbreviated. This gives a clearer overview per layer. But makes the use of the different strategies more difficult. The meaning of each abbreviation has to be reviewed somewhere else.

However, the transition towards Circular Industrialised Construction can be difficult and challenging. Applying the different strategies per layer can be an effective method in transitioning towards Circular Industrialised Construction. This layer-by-layer approach is still challenging but allows for guidance in the difficult prospect of circularising a fabrication process.
Additionally, this framework can be applied to companies that want to transition towards Industrialised Construction, Circular Building or want to start integrating both in their business process. Instead drastically overhauling the entire business process. Incremental improvements can be applied that eventually result in a circular business process.

Nevertheless, the framework remains difficult in its usage. The different strategies still require certain distinctions in the application. To accurately react to the distinctions experience with the different layers and strategies results in an enhanced outcome. This means that inexperience can result in underwhelming outcomes. Thus hindering the application of Circular Industrialised Construction. The framework can help in building awareness about the challenges in the application of the different layers and strategies and how these are interconnected.

7.5. Research Limitations & and recommendations

The research that was executed was under a strict schedule. This has affected the research because it resulted in not all phases of the research being executed. Phase 3 of the research, presenting and discussing the framework with a focus group was not executed.
The ability to test and present the framework with industry professionals would have benefited the research. Those active in the industry could have contributed to the framework by discussing certain nuances that impact the execution of the strategies. Obtaining feedback from the focus group would have validated the framework significantly.

The selected case companies (CitizenM, Daiwa Modular Europe and Home.Earth) fitted the research accordingly. In specific the three distinct characteristics that were always attributed to two case companies allowed for the comparison. However, a limitation as a result of a selected case company did affect the research.
The limitation that affected the research was how far along the process of developing Circular Industrialised Construction buildings Home.Earth was. The fact that they were not yet operating and maintaining their first circular and industrialised building made it difficult to discuss these phases. Potential pitfalls and difficulties in those phases could not be discussed only hypothesised. But the nature of pitfalls and difficulties is that you do not expect them to surface. Additionally, the tenant structure they envisioned and how this affects the maintenance and operation was difficult to distinguish. For a more complete outcome and comparison between the three case companies Home.Earth should have had more experience.

Lastly, the recommendations for future research. Two new research projects will be proposed here, besides the research project in which Home.Earth and the Delft University of Technology already collaborate.
The first new research project is related to the deposit arrangements Daiwa Modular Europe makes when developing buildings. The exact details, expected levels of trust, duration and other aspects associated with this project are worth reviewing.
The second new research project relates again to Daiwa Modular Europe. Over a year and a half Daiwa Modular Europe needs to relocate a building in Amsterdam since the lease on the patch of land expires. This project, the Ravel Building,

Figure 7.1: The Ravel residence, located in Amsterdam, needs to be relocated within 5 years

contains over 800 studio units(figure 7.1). This happens on a size and scale not yet executed by Daiwa Modular Europe and so far they are aware of other projects. This can become a unique first.

8 Conclusion

At the start of this research, the concepts of Circular Building and Industrialised Construction were introduced. The concept of Industrialised Construction has been discussed extensively in preceding articles and reports. For this research, the phrase Industrialised Construction is considered a more holistic terminology that aims to improve the (resource) efficiency of the building process. To sufficiently place the concept in practice the application of Industrialised Construction comes down to standardisation. This can subsequently be explained as constructing standardised modular building elements, in an off-site factory setting, that are assembled on the project site.
The concept of Circular Building has also been discussed extensively in articles, reports and books. The phrase Circular Building comes down to efforts to reduce the environmental impact of the Built Environment. These reductions can be achieved by designing and building modular houses, reducing the energy demands of buildings, reusing materials in other buildings and making use of building materials that capture co^2. In practice, this means that buildings are often designed as modular elements that can be disassembled or deconstructed.
Combining these two concepts, Circular Building and Industrialised Construction, results in the concept of Circular Industrialised Construction. This concept can offer a solution to the waste production, productivity decrease, energy consumption and co^2 production of the construction industry. These solutions can be implemented by scope adjustments in the design process. In practice, the concept of Circular Industrialised Construction comes down to producing Circular Building in an off-site factory setting. These Circular Buildings can be disassembled or deconstructed and reused in new building projects.

Research has been done into the separate concepts. However, very little was known about how Circular Industrialised Construction impacts the operation, maintenance and End-of-Life of these buildings. Reviewing strategies implemented by the case companies on the operation, maintenance and End-of-Life phase of these buildings could result in valuable insights.
Therefore the main research question that was answered in this research is:

"How can strategies for circular buildings using industrialised construction methods account for the operational and End-of-Life phases?"

To answer the main research question, several sub-research questions have been developed. The sub-research questions were:

1. *What strategies for Circular Building using Industrialised Construction methods can be identified?*

2. *How are the operation and End-of-Life phases taken in consideration during the strategy-making process?*

3. *What are the pitfalls in the strategy-making process for the operation and End-of-Life phase of circular buildings using industrialised construction methods?*

To reiterate, the first sub-question was: *What strategies for Circular Building using Industrialised Construction methods can be identified?* Several strategies for Circular Building using Industrialised Construction methods can be identified. An overview of the identified strategies can be found in Chapter 5 (Figure 5.2). The most notable strategy is insourcing the design process. This approach has been implemented by all three case companies. The method of Industrialised Construction and thus standardisation reaps the best results when improvement to design iterations can be implemented. An effective method of assuring these iterations in the design are implemented sufficiently is taking charge of this process.

Another, strategy that was identified was developing feedback loops with the manufacturing process or department. All three case companies reported that the design departments have close connections with the manufacturer. Whether they outsourced or insourced the production their collaborative relationship with this phase of the circular design process allowed the design departments to improve designs before production.

Similar feedback loops were identified with the operation and maintenance departments of the case companies or clients of the case company. Feedback provided by these departments influenced design decisions taken by the design team. In Chapter 4 several design teams mentioned that the rate of replacement for components influenced their design choices. They for instance asked for feedback on how often some parts needed to be accessed and this impacted the coverings for these parts.

The second sub-question was: *How are the operation and End-of-Life phases taken into consideration during the strategy-making process?* The operation and End-of-Life phases are taken into consideration in four distinct ways during the strategy-making process.

First, the operation and end-of-life phases are taken into consideration in the strategy-making process by selecting and contracting suppliers that offer to take back their supplies when they are broken or soiled. This requires suppliers that are willing to contribute to the circular goals of these companies. Procuring these suppliers in the strategy-making process is valuable.

The second method in which the operation and end-of-life phases are taken into consideration is by implementing design principles that allow for ease in the replacement of components. This resolves around design for disassembly but also design for accessibility to components. Being aware of the impact design choices have on the operation and maintenance phases of the building needs to be considered during the strategy-making process.

The third method that takes the operation and end-of-life phases into consideration during the strategy-making process is incentivising tenants to properly or adequately use components of the building. Rewarding proper behaviour with financial rewards can result in fewer maintenance requirements over the lifetime of buildings. This method is taken to prolong the lifetime of components in the building. This is an important aspect of the strategy-making process.

The final method in which the operation and end-of-life phases are taken into consideration during the strategy-making process is deposit arrangements on building components. These deposit arrangements do not exist between the owner and the tenant but between the developer and the client (Owner/operator) of the building. After the ending of a lease agreement, the building components are taken back by the developer in return for a predetermined sum of money.

The third sub-question, is restated here: *What are the pitfalls in the strategy-making process for the operation and End-of-Life phase of circular buildings using industrialised construction methods?* This is answered by the following pitfalls that were identified.

The first identified pitfall relates to the difficulties in gaining approval from government agencies. In specific the decentralised nature of the governmental organisations. Elements, components and entire units often have to be subjected to the same manner of scrutiny when these are designed for another municipality. The scrutiny can be related to the building code, fire regulations or other certifications. Often identical products have to be checked multiple times by different municipalities or governmental organisations. This wastes material resources and also delays the process unnecessarily. Resulting in projects that take longer than necessary.

The second identified pitfall in the strategy-making process for Circular Building using Industrialised Construction methods is the structural deformation during transport. Structural deformation during transport can result in significant cost increases due to altered structural stability. Consequently, the moisture and vapour proofing can be nullified. This is a pitfall in the strategy-making process since the experience in transporting or moving Volumetric components can be an important decider in selecting a transportation partner.

The third identified pitfall that affects the strategy-making process is the ability of the design team to consistently adhere to the developed concept. Even slight and incremental changes in the dimensions of components can result in several

versions of components that need to be stored in case of repairs. This is a pitfall because it can be very beneficial for the business case to develop a few square meters extra in each room. In the end that will only result in increased maintenance and operation costs.
The fourth identified pitfall in the strategy-making process is selecting manufacturing partners based on cost-effectiveness or other deciding factors that limit a collaboration process before, during and after manufacturing. Selecting partners that share an understanding of the collaboration required are most likely able to further develop the product in not only the manufacturing process but also all the other phases of a building.
The penultimate identified pitfall is selecting suppliers that do not support a circular approach to the products they deliver. Ensuring that furniture can be repaired, replaced and/or refurbished can reduce the environmental impact of the building. Selecting suppliers that do not offer a repair, replacement or refurbishment service results in furniture being transported to landfills.
The last identified pitfall is the time of construction. Regardless of the amount of feedback loops integrated into the design process, the construction of a building requires a significant amount of time. As a result, a newly finished building is already outdated. This difference between design completion and construction completion means that valuable iterations are often implemented a year to two years later.

At last, the main research question will be answered. To reiterate, the main research question is: **How can strategies for circular buildings using industrialized construction methods account for the operational and end-of-life phases?**
Strategies for Circular Buildings using Industrialised Construction accounts for the operation and end-of-life phases by comprehending the following aspects. First, taking charge of the design process is a valuable enabler of Circular Industrialised Construction. In addition, the integration of feedback loops of all the different departments that are affected by design decisions creates incentives that consider a different perspective.
Integrating and organising circular loops can be created regardless of the business organisation. Owner/operators have more intrinsic motivations to create circular loops with their suppliers. This can be organised by selecting suppliers on the agreement that they take back their products at the end of their lifetime. Developers who do not have these incentives can organise the circular loop with clients by providing deposit arrangements on structural components of buildings that last for the lifetime of the component.
Pitfalls to be aware of during the strategy-making process are reoccurring government procedures and regulations that have to be addressed in each municipality again and again. Another pitfall to be aware of is the chance of structural deformation during transportation. Thus selecting partners that have the skill and ability to prevent is vital. The last identified pitfall is the length of construction. Once a building is completed the designs are often already a few iteration old.

9

Reflection

Relation research and master program
The Circular Economy principles have been a relevant aspect of the master's program, Architecture, Urbanism and Building Sciences. Within the track Management in the Built Environment the aspects related to the Circular Economy have been taught. In particular how the front-end of the building process impacts buildings. This perspective has been a guiding principle in the research.
The aspect of Industrialised Construction has barely been addressed in my master's program. Only during the orientation of a research topic the concept of Industrialised Construction has been introduced. This introduction only occurred after some initial research into the impact of Industry 4.0 on the construction sector.
This is a missed opportunity for the faculty and the University. An organisation that has a mission statement: "**impact for a better society**" should have introduced these topics and the several aspects that limit the application long ago. The master program would benefit from courses that promote and discuss Industrialised Construction. For instance teaching students about methods for supply-chain integration or early involvement of supply-chain actors.

Relation between research and design
The research actively researched the impact of design on the Circular Economy and Industrialised Construction. In particular how design choices impacted the circular aspirations of the case companies. But, maybe more importantly, how they strategise to achieve their circular goals. What methods the case companies have developed within their business and what methods the case companies employed in their collaboration with actors and partnerships?
The relation between the research and the act of designing lies in the strategy framework that was developed. The framework was designed to provide different actors in the industry an overview of strategies that can be applied in the application of Circular Buildings that are constructed through Industrialised Construction
The development of the framework has contributed to the synthesis of this research by reviewing the collected data. The development contributed to highlighting the existing pitfalls existing in the application of Circular Industrialised Construction. I have struggled with identifying the pitfalls throughout the process. But in designing the framework I have realised that to mitigate some barriers several strategies have been developed.

Approach and methods
During the research, the selected approach and methods suited one of my personal research goals. All these companies are boasting about their circularity efforts and how they are reducing their impact. But how do these companies do that and how circular is it really? Reviewing these companies has impacted my view on the circularity of the built environment. I think that the approach of semi-structured interviews with employees of the case companies suited the research well. However, the risk of interviewees answering the questions based on what they expect is the right answer has always been a risk. To mitigate this risk I have tried my best to create a relaxed atmosphere and tried to start and continue a conversation with the research participants.

Value and implications
The value and implications of the research relate to the societal relevance of the research. With an expected need for more housing in the upcoming years, the application of Industrialised Construction in the Netherlands will remain of importance.

Therefore the research into Industrialised Construction has and will remain of value. However, the value and implications on the Circular Economy, although still valuable, might be affected due to a recent shift in political values. At the start of this research, the expected development of Circular Building in the Netherlands was positive. The assumption was that the developments would contribute to a healthier Built Environment. Reductions in co^2 emissions could combat potential climate change. Therefore research into the subject of the Circular Economy was encouraged because companies would eventually have to shift towards a circular approach due to governmental regulations. With the overall political discourse in the Netherlands shifting away from parties that want to combat the climate crises. The responsibility of Circular Economy principles in the Built Environment lies eventually at the companies, as a scientific community we can argue that Circular Building is possible and reaps benefits for the environment. If those decisions are not encouraged and even haltered we may have to put our Circular Economy aspirations aside for a while.

Transferability

The transferability of the research has been guaranteed by collecting and saving the data. The research methodology has also been described and thus can be repeated. The transcripts of the interviews will be stored to repeat the research. This is a result of the fact that the research is subject to the relationship that was developed between the interviewee and the researchers. A different researcher might produce different results with the same interviewees.

Reviewing the framework with industry specialists would support and contribute to the credibility of the research. Supplementary research in the subject of Circular Industrialised Construction would support further developments.

Personal reflection on the process and outcomes

The entire graduation process has been widely confusing and profoundly challenging. The search for a topic, supervisor, second supervisor and research gap has been ambiguous. The amount of decisions and questions I needed to answer were very challenging and I did not enjoy the decision-making process at all. During that process, I often wondered why this was all necessary. While writing the last words of the research for the P4 presentation I have to admit, I get it. The decisions I have made were impactful and progressed my research.

Although I often thought that the P2 was an unnecessary hoop I needed to jump through to progress with the graduation lab. I realised that it actually sets up the research and that it can guide your progress significantly. Failing to extract the most of that phase remained an issue in the entire process. I do not like to admit it, but repairing my P2 was necessary. I think the entire process and concept has been in my head but not yet fully formed. Transitioning those thoughts into actual words on paper resulted in me being forced to make decisions that impacted my research.

The P2 that was awarded a pass was framed rather ambitiously. The expected time and the available time did rarely match up. I was aware of this from the start, I think I even considered this in the P2 report. Nevertheless, the P2 pass resulted in a sense of achievement and excitement since I could progress to the next stage.

The collecting of the data through interviews with industry professionals has been an enjoyable part of the research. The conversations often resulted in new insight and valuable attributions to the research. The discussions with the supervisors similarly have been a part of the research I have been looking forward to. These discussions and clarifications often resulted in me realising that I was not doing this research on my own.

Towards the P3, in my conversations with my supervisors, I was made aware that this presentation was just a progress update. The main message in preparing for this was: ”Nothing to worry about, but it will confuse you”. And that is completely true. It did confuse me. The confusion was a result of the fact that not all the data was collected. The most contradictory of the P3 is that you want to do a good job, but you also know it takes away valuable time.

Working towards the P4, finalising the results framework and working on figures and illustrations has been the most challenging part for me. I often disliked the process and am relieved that I have done most of the work for it. I started the research project by aiming to score an 8. However, now I am here, close to the end of the research, I will settle for a 6. It has been challenging and less and less enjoyable as time progressed.

Often on my way home after a hard day of work, I tried to answer the question of why I did not enjoy this part. For other courses, the writing phase was also often part of it and I did not despise it that much. You would often work on these tasks together. And I think this is what has been lacking

with me in this research process. The fact that I have to do this all by myself.
How do I look back on the outcome of the research, framework, and collected data? I think I am proud, and that the outcome warrants the research. I think that the fact that most companies despite their best aspirations are not as far along the circular transition as they want us to believe. Pinpointing that and questioning their efforts has offered an interesting new perspective on the situation.
As I reflect and mostly consider my efforts on this research process, 1 question does come to mind: ”Would I do this all over again?”. Two weeks ago I would have wholeheartedly said no in bold capital letters with at least three exclamation marks. However, as I continue to reflect on this process I must admit. I would do it again. I think that the research outcome warrants that. The knowledge acquired needs to be shared across the sector to effectively transition the construction sector into a sustainable future.

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