Implementing the Principles of Circular Economy in the Construction Industry

A framework for the construction industry practitioners to accelerate the systematic transition into circular mode of operation: Meta Narrative Review

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Preface

This thesis is the culmination of over 8 months of research on the topic of Circular Economy in the construction industry. This has been an incredibly challenging but also enjoyable experience that gave me an opportunity to combine my interests in construction and circularity.

Ever since I can remember, I have always been intrigued about buildings and construction which has made me aspire to become an architect since a young age. After gaining an opportunity to study my passion back home in Georgia, I quickly learned that I was drawn to the technical aspects of the profession with my favorite subjects being relater to material sciences or building physics. Throughout my educational journey I have leaned into this interest broadening studies to structural design in TU Eindhoven. Later I expanded my repertoire even further in TU Delft where I began studying the processes taking place in the entire construction industry. Here I found my passion for learning and wanting to understand all aspects of construction.

During my education, sustainability was a topic that has appeared more than once and caught my attention. Particularly the concept of regenerative design made me exited thinking about the ways to transform the modern world into a system that can not only sustain the current operation but further regenerate. With these interests I wanted to work on projects that not only envisioned an ideal future but also developed the steps to get there.

After long research process I present the fruits of my labor that give insights on how the construction industry engages or can engage with circular operations, what are the barriers preventing the further implementation of CE, and what are the enablers that can be used to overcome the challenges. The results give a comprehensive overview of all the relevant factors influencing CE in the construction industry and can ideally be used as a framework for the industry practitioners that want to integrate circularity principles in their work.

I am incredibly grateful for this experience where I not only had to use all of my accumulated knowledge to produce this thesis but also learn about my personal habits and improve them. I want to express my gratitude to my graduation committee. I can't imagine being an easy student to mentor especially under the scenarios that happened through the process, and I am truly thankful for your patience, guidance, and experience. I want to thank my graduation chair Ad Straub for your assistance during the difficult times. I cannot thank you enough for the way you have continuously reached out and checked up on me, for connecting me with relevant people, and for always giving me advice. I want to express my gratitude to my supervisor Erik-Jan Houwing for always asking the right questions and making me think about solutions instead of just delivering them. Your critical insights and continuous feedback were essential for this research.

Besides the academic staff I want to express my gratitude to my friends and family. A special thank you to my girlfriend Ana for keeping me motivated during difficult times and sticking by my side when I needed it the most. Thank you to my parents for giving me the opportunity to go through this journey and staying patient and supportive despite the difficult times.

I hope you enjoy reading!

Levani Mikaberidze 2025

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Executive Summary

Introduction

The construction industry is one of the most resource intensive and polluting sectors in the world. It accounts for nearly 40% of the global CO2 equivalent green light gas emissions, contributes to a third of the global energy use, and requires large quantities of raw materials (Regúlez et al., 2022) (Cabeza et al., 2022). With the increased demands for infrastructure and construction due to the trends of population growth (*United Nations*, 2022) and urbanization (*Statista*, 2024), it is no longer possible to follow the traditional linear "take-make-dispose" economic models, as the planet Earth cannot sustain humanities unsustainable consumption patterns (Rockström et al., 2009).

This research introduces the concept of Circular Economy (CE) as a promising alternative that could allow the construction sector to keep up with the high demands while reducing its negative impact on the environment (Rijkswaterstaat et al. 2022) (Mhatre et al., 2021). This is done through envisioning a regenerative economic system that focusses on resource loops, maximizing the resource efficiency and allowing for elimination of waste through retention of the high value in the used materials (Bocken et al., 2016) (Ghisellini et al., 2016). Despite the promising nature of the presented concept, the research shows that its widespread implementation in the sector is very limited (Ghufran et al., 2022) (Ghisellini et al., 2016). This was tied to the lack of incentives for transitioning in this new way of operation (Ding et al., 2023), which was particularly evident in the construction industry where, as suggested by Adams (2017), CE implementation is at its infancy. Looking deeper into the issue of limited implementation, the report has identified following challenges:

- CE frameworks have been developed in other industries focusing on reuse and recycling of short and medium-lived consumer goods such as clothing and lack the nuance for addressing the complexities of the construction industry (Minunno et al., 2018) (Lee et al., 2023) (Eberhardt et al., 2020) (Pomponi & Moncaster, 2017).
- There is a lack of globally recognized standard for CE in the construction industry (Banihashemi et al., 2024) as well as no clear definition of the topic (Mhatre et al., 2021). This creates uncoordinated efforts for CE development seen in the research going in many different directions without a unified overarching goal (Eberhardt et al., 2020).
- The industry lacks the knowledge and experience to operate circular construction processes (Brown et al., 2021) while there seems to be a large disconnect between the academia and practice. This creates a paradoxical environment where the new projects cannot be completed due to the lack of experienced actors and the actors can't get experience due to the lack of circular projects.
- The research about CE topic puts too much emphasis on the specific principles such as loop thinking (Bocken et al., 2016) (Jansen et al., 2020), while lacking the understanding of the necessary strategic interventions necessary for achieving industry wide transition (Mhatre et al., 2021) (Adams et al., 2017).

This thesis gives a solid base of information touching upon all the important topics that come in play while trying to achieve an industry wide transition into a circular mode of operation.

Research objective

The research has two primary objectives: 1. Developing a strong understanding and documenting the available information about the topic of CE in the construction industry to give the most comprehensive overview of the challenges and the opportunities that can be used for devising strategic interventions in this thesis and the future research, 2. Creating preliminary strategies that can overcome the key barriers of CE adoption. These objectives are achieved through answering the following research question:

RQ: How can the construction industry accelerate the sector wide transition into a more circular way of operation using the principles of Circular Economy?

Due to the complexity of the explored issue, the main question was broken down in the following five sub-questions to tackle the specific aspects in a structured manner:

SQ1: What does the Circular Economy entail in the context of the construction industry and how is the concept utilized in modern construction practice?

SQ2: Who are the stakeholders involved in the construction industry and what power do they hold over adoption of a CE?

SQ3: What are the most important barriers that limit the widespread adoption of CE practices in the construction sector that halt the industry wide transition?

SQ4: What are the enablers that can enhance the widespread adoption of CE in the construction industry?

SQ5: What is the relationship between the barriers, enablers, and the actors of the construction industry and how can these connections be utilized to accelerate the industry wide transition?

The research takes a sequential approach in answering each of the given questions, this meant that each answer was built on the previous findings, allowing for backtracking on the available findings and refining conclusions.

Methodology

The paper has taken a Systematic Literature Review (SLR) approach to the research analyzing 59 academic papers. This methodology was chosen to combine both complementary and conflicting data giving overarching narratives and limiting personal bias (Wong et al., 2013). The process was conducted in a structured manner in two phases: 1. The first phase was used to gain a general understanding of the topic of CE which was used to formulate the research plan, 2. Second phase includes the main research of the paper looking at the context of construction industry, barriers, and enablers.

Each step of the research process was meticulously constructed and documented according to the RAMESES publication standards (Wong et al., 2013). This framework is a complementary tool for a systematic approach to the literature review which gives a list of 20 rules presented in table 1 for the research and analysis. With this, the thesis aimed to adhere to the highest standards for transparency, allowing the reader and the future researchers to understand the rationale behind every decision and validate the findings.

Results and analysis

The research has identified various interesting insights about many topics. The paper presents all the findings in a sequential manner following the list of sub-questions.

The paper first defines the context of the circular economy and the construction industry by addressing sub-questions 1, 2, and 3. Here the research has explored the origins and the goals of the concept of circular economy and its past applications. It also looked at the inherent characteristics of the construction sector, its lifecycle, and the current state of the area of CE in the industry. This information was combined to define a construction industry specific definition of CE which is as follows: "A construction designed, constructed, used, and reused with the entire lifecycle in mind. It is assembled with optimal materials that are produced in a closed loop system in a manner that allows for easy deconstruction. The construction is an economically responsible, efficient product with an optimal balance between the embodied energy and operational energy use while providing a comfortable environment for its users. It is powered by renewable energy sources and is maintained in an efficient manner to retain the value of the used materials allowing for future reuse of the building components and materials keeping resources in a closed loop.". The given definition is an important finding that was used as the baseline for the report when developing solutions for the sector. Following this, the thesis aimed to finalize the contextualization of the construction sector by looking at its stakeholders. Here, through meticulous literature review, the research identified 12 of the most relevant actors of construction that are later used in the development of strategic interventions.

After defining the context, the research moved its focus to gaining an understanding of the problems by answering SQ3. Here the research found the most influential barriers of CE adoption in the construction industry by backtracking on the previous findings and analyzing the academic literature. In total the two methods resulted in a list of 146 barriers, which was cut down to 10 after evaluating their relevance on the 4-quadrant model in accordance with the factors of: 1. Number of appearances in academic literature, and 2. The quantity of interconnections with other relevant barriers. With this the report answered SQ3 and moved onto exploring the opportunities by answering SQ4. Here the paper followed similar methodology to the research of barriers and resulted in a total of 209 enablers. After removing the duplicates, this list was cut down to 47 enablers. These opportunities were not evaluated based on their relevance as their importance relied on the addressed barriers.

With all the necessary information in place, the thesis categorized the findings in the previously designed frameworks to simplify the process of matching the variables. Here the barriers, enablers, and stakeholders were grouped based on their effect on the construction industry looking at what areas did they influence and their relevance across the different phases of the construction projects' lifecycle. After this, the general, 5 step, approach was created for developing strategies to address the barriers. Next, with the use of the given information, the research has developed 10 in-depth preliminary strategies for each of the 10 relevant barriers. With this the paper finalized answering SQ5.

Discussion and Conclusion

The thesis has found various interesting insights about the concept of CE and the way it is used in the construction industry. The paper created a large base of knowledge about the context of the construction sector, the barriers it faces, and the enablers it can utilize to accelerate transition into a circular mode of operation. Using the combined information the paper devised a general framework for overcoming the barriers and used it to give 10 specific preliminary solutions.

Due to the complexity of the main RQ, the paper does not recognize the final results to be a comprehensive answer, but the delivered results are satisfactory for giving a basic answer while providing a strong foundation for the future research to build up from,

Recommendations

For future research, the paper recommends validating the findings of this thesis to ensure their credibility. Additionally, it recommends a more structured way of literature research to take a more comprehensive approach and include all the available information.

Moreover, the research recommends conducting deeper, more specific analysis of each of the barriers to increase the understanding of the opportunities. Additionally, future research needs to look into other industries that utilize CE and work with the actors to learn from them and apply unique solutions to the construction.

Finally, the research recognizes the disconnect between academia and practice, and advocates for applying theoretical knowledge to real-life construction. This way it is possible to gain a more nuanced understanding of CE in construction.

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List of abbreviations

BIM – Building Information Modelling

CDW - Construction Demolition Waste

CE – Circular Economy

CITG – Civil Engineering and Geosciences

CME – Construction Management and Engineering

DFD – Design for Disassembly

EE – Embodied Energy

EOL – End of Life

EU – European Union

GHG – Green House Gass

ICER – Integrale Circulare Economie Rapportage (From the reference article)

LCA - Life Cycle Assessment

NCEI – National Center for Environmental Information

RFID Radio Frequency Identification

ROI – Return on Investment

RQ – Research Question

SDG – Sustainable Development Goals

SLR – Systematic Literature Review

SRQ – Sub-Research Question

UN – United Nations

1. Introduction

1.1 Background information

Recent history shows a rapid development of humankind resulting in major quality of life improvements for the majority of the population. Progress in the industrial processes alongside technological developments has made it possible to overcome many of the challenges humans faced in the past by providing the most essential needs such as food, water, and shelter. Today, advancements in the fields of infrastructure, transportation, and energy make it possible to further subdue nature, making what was previously unimaginable possible, but such achievements have come at a major cost.

Unfortunately, for the first time ever, humanity has reached the development at a planetary scale, making the Earth's boundaries, such as finite resources, the primary limiting factor for further advancement (Rockström et al., 2009). Despite the clear warnings from environmental sciences about the limitations of the planet, the consumption patterns of humanity largely remain unchanged, leading to Earth being pushed beyond its safe operating boundaries. The largest damage appearing in the areas of climate change, biodiversity loss and the global nitrogen cycles (Rockström et al., 2009).

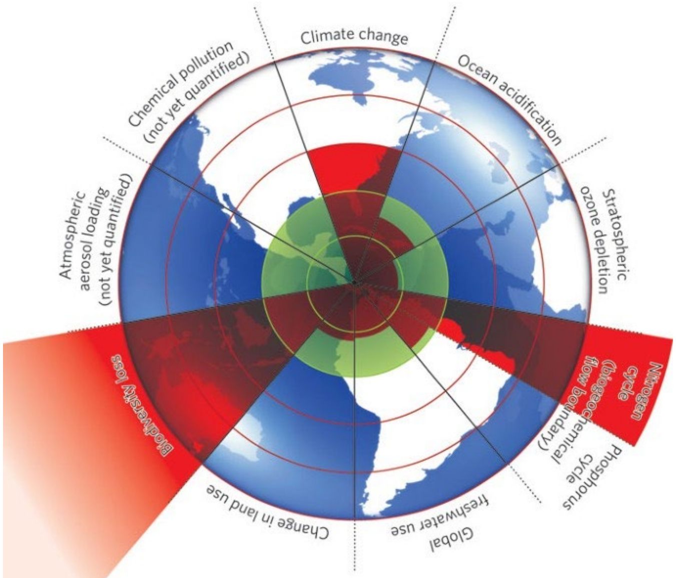


Figure 1. Earths boundaries (Rockström et al., 2009).

The consequences of the careless and unchecked development of humanity have become impossible to ignore. Climate change has resulted in increasingly frequent and severe extreme weather conditions alongside a steady rise of global temperatures (United Nations, 2024). The past decade (2014- 2023) was the warmest ever recorded, while 2023 has shown the highest average global temperature since 1980 (NCEI, 2023). Additionally, UN (2022) has recorded increases in severity and frequency of storms, droughts and the decreased water availability which has a cascading effect on many industries such as agriculture, health, and built environment (NCEI, 2023).

Despite such drastic effects on the climate, human resource consumption and pollution only grow with rapid population growth. Currently, the planet counts roughly 8 billion human inhabitants, projected to grow to 9.7 billion by 2050 and 10.4 billion by the end of the century (*United Nations*, 2022). Such surge in global population combined with the ever-rising trend of urbanization, which is projected to reach 70% worldwide by the end of 2050, raises concerns about factors such as housing shortage and further material depletion (*Statista*, 2024).

The housing sector poses a particularly high concern given the current state of the global housing market, with regions such as the European union (EU) facing a mismatch between supply and demand. Additionally, there is a notable shortage of quality affordable housing which puts many families in a position where they struggle to satisfy their basic need for shelter (Henley, 2024). Countries such as Netherlands have already responded to the crisis by setting ambitious goals for new construction to satisfy the demands (*Circle Economy*, 2022). However, this approach places further strain on the planet's finite resources.

One thing is clear, in order to keep up with the consumption patterns of humanity in the coming years due to population growth and urbanization it will be necessary to increase supply, but this will likely only put more strain on planet Earth.

The construction industry, which provides essential services for the modern world such as housing and infrastructure, is one of the most polluting sectors globally. It accounts for nearly 40% of the world's CO2 equivalent greenhouse gas (GHG) emissions, a third of global energy use, and is a primary consumer of water and sand, two of the most used materials worldwide (Regúlez et al., 2022) (Cabeza et al., 2022). In countries such as the Netherlands, that are seeing increased construction to meet the housing demands, construction alone consumes up to half of the total raw materials used in the country, alongside accounting for 40% of the total energy consumption, and third of the water consumption. Additionally, it generates a third of a country's total GHG emissions and produces 40% of the total waste (*Circle Economy*, 2022) (Rijkswaterstaat et al. 2022).

The abovementioned challenges are tightly coupled and are impossible to resolve separately, forming a typology of issues that can be categorized as "wicked problems". The construction industry plays a crucial role in finding a solution, offering opportunities in reduction of GHG emissions, energy use, and waste production as well as material use (Pomponi & Moncaster, 2017). Currently, the construction sector can be considered outdated and ineffective in addressing such complex challenges (Brown et al., 2021) showing a dire need for a systematic change from the traditional linear way of construction (Rockström et al., 2009) (NCEI, 2023) (United Nations, 2022) (United Nations, 2024).

Over the years, sustainability has emerged as a primary strategy to combating the ever-growing environmental challenges. Global agreements such as the Paris Agreement (Rogelj et al., 2016) and united nation's (UN) sustainable development goals (SDGs) (*Sustainable Development*, z.d.) have aided in shaping policies aimed at waste reduction and increased resource efficiency (Ghisellini et al., 2016).

Within the construction industry, the EU and its member states have set ambitious goals to reduce the environmental impact of structures (Kanters, 2020), for example, net-zero buildings by the end of 2050 (Wielopolski & Bulthuis, 2022). Such initiatives have resulted in various strategies aimed at reducing energy use during the operation phase of constructions (Eberhardt et al., 2020). Unfortunately, such a narrow focus has led to the unintended consequence of shifting the environmental impact from one stage of construction to the other (Pomponi & Moncaster, 2017). With the improvements in the operational stage of structures' lifecycle, the embodied energy (EE), which is the energy used for production of components and materials from the mining of its components up to the use, now accounts for to up to 45% of the total environmental impact (Kanters, 2020). Currently, it is necessary to shift away from the current system that puts a significant focus on improvements at the operational stage of construction projects into a lifecycle-based approach that includes all aspects of production, construction, transportation, maintenance, and disposal of the building materials to address the issues more efficiently. To meet the ambitious goals of the Paris Agreement (Rogelj et al., 2016) and SDGs (*Sustainable Development*, z.d.) and make sure that they don't fall short, like many of the past sustainability related practices, it is necessary to adopt a more holistic approach to tackling the climate crisis (Wielopolski & Bulthuis, 2022).

The circular economy (CE) is a promising concept that could help address many of the issues faced by the construction industry. It is an emerging trend that was popularized by the Ellen MacArthur foundation, which could provide a tangible solution to the challenges of climate change by envisioning a regenerative economic system and offering tools to address environmental issues while promoting sustainable development (Bocken et al., 2016) (Rijkswaterstaat et al. 2022) (Ghisellini et al., 2016) (Mhatre et al., 2021). Unlike the traditional linear model of "take-make-dispose", CE focuses on the resource loops, maximizing the resource efficiency and limiting waste by focusing on retaining the highest possible value for the resources in the economy (Bocken et al., 2016) (Ghisellini et al., 2016).

While the concept can be considered relatively new, CE principles can be seen in many of the global documents such as SDGs, and on a smaller scale national goals such as, for example, commitments from the Netherlands to abolishing the use of abiotic raw materials by the end of 2050 (*ICER*, 2023). However, despite the clear potential of the concept which can be seen in successful pilot cases, its widespread implementation remains limited (Ghufran et al., 2022) (Ghisellini et al., 2016) (Afshari & Górecki, 2019). This is likely due to the lack of incentives for transitioning the current linear supply chains into Circular Economies (Ding et al., 2023). This is particularly evident in the construction industry where, as Adams (2017) suggests implementation of CE principles are at its infancy.

1.2 Knowledge gap

The construction industry can benefit significantly by the adoption of the principles of CE given its substantial environmental impact and polluting nature (Afshari & Górecki, 2019). The Ellen MacArthur foundation (2022) even quantifying these benefits, stating that systematic implementation of CE principles could result in up to 38% reduction in CO_2 emissions by 2050 (Ellen McArthur Foundation, 2022). However, despite the potential of the CE as well as the growing interest in sustainable innovations in the construction industry, the speed at which they are implemented into practical and scalable solutions remains far too slow (Wielopolski & Bulthuis, 2022) and the business-as-usual approach is still deeply entrenched within the industry

(Eberhardt et al., 2020). There are several factors that contribute to the underutilization of CE principles.

Firstly, while CE principles have been gradually explored and successfully applied in various fields, their development is far slower in the construction sector (Lee et al., 2023) (Minunno et al., 2018). Current research on CE often focuses on the concepts of reduction, reuse, and recycling of the short and medium-lived consumer goods such as electronics and clothing but lacks development for a long-lived asset such as constructions (Minunno et al., 2018) (Lee et al., 2023) (Eberhardt et al., 2020) (Pomponi & Moncaster, 2017). Unfortunately, solutions created for consumer goods fall short when applied to the construction industry. Construction projects are far more complex, dynamic, unique, and with a longer lifespan. They are composed of a multitude of different materials, each with their own lifespans, and characteristics, while interacting with the entire system (Eberhardt et al., 2020). In the words of Eberhardt (2020) existing CE guidelines fall short as they fail to match the complex nature of the construction industry, resulting in inadequate use/development of CE-focused design and collaboration tools with their main application being limited to the use of byproducts in material production and recycling (Minunno et al., 2018).

Moreover, the shortcomings of CE in the construction industry result in a lack of globally recognized standard (Banihashemi et al., 2024) and lack of clear definition of the concept that creates ambiguity (Mhatre et al., 2021). Such ambiguity results in CE initiatives going in many different directions and with varying focus areas such as, for example, Design for disassembly, material choice, flexibility etc. (Eberhardt et al., 2020). This fragmentation gets in the way of universal adoption of CE principles in the construction industry and creates the need for better understanding and clear definition of the concept within the sector (Eberhardt et al., 2020) (Adams et al., 2017). The construction industry of the Netherlands can be viewed as a clear example of the issues related to the ambiguous definition of CE. The country recycles up to 88% of all construction demolition materials and, at first glance, can be seen as a pioneer of CE, but upon a closer inspection, the majority of the recycled materials get "downcycled" reducing their inherent value. Such loss of value results in limited reuse of the materials, in this case only 8% of the construction material comes from the secondary sources (*Circle Economy*, 2022). A different approach to CE is necessary to overcome the issues stemming from such ambiguity.

Another issue lies in the lack of experience of the construction practitioners in dealing with the new ways of operation as well as the disconnect between academia and practice. According to Brown (2021) most companies are still inexperienced in the CE field and are incapable of operating all the aspects that come with circular practice. This creates a loop of actions that halts the new construction projects moving towards CE, which, in turn, limits practitioners' ability to acquire necessary experience. It is necessary to find ways to connect upstream and downstream actors to facilitate necessary information exchange that would allow circular practice (Brown et al., 2021) (Adams et al., 2017). According to Lee (2023) It is particularly important to keep up with the recent studies about the topic of CE as it is not only beneficial for the business and academia for carrying out follow-up research and development, but it can also act as the basis for both formulation and modification laws and regulations.

Finally, while there is a body of literature focusing on the principles and strategies of CE such as R strategies and loop thinking (Bocken et al., 2016) (Jansen et al., 2020) (Reike et al., 2018), there seems to be limited information about the necessary strategies for comprehensive, systematic implementation of circular economy within construction (Mhatre et al., 2021) (Adams et al., 2017). Such narrow focus of the research can be attributed to the complexity of the topic with academia prioritizing in-depth understanding of components of CE but overlooking a much more complex bigger picture. Ideally, CE should involve the entire supply chain across the entire lifecycle of the construction system (Banihashemi et al., 2024) with a comprehensive approach to maximize the possibility of achieving the goals of circular economy.

1.3 Problem statement

The increasing demand for construction, driven by the trends of rapid population growth and urbanization in combination with the impending climate crisis, gives the construction industry a significant challenge to overcome. The sector is tasked with inventing a new way of production that will allow it to keep up with the increasing demand while minimizing the pollution to offset the burden on the planet.

While there have been various attempts at overcoming this issue, most notably with the concept of sustainable development (Rogelj et al., 2016), or the net-zero building initiatives in the construction sector, the industry still lacks a holistic approach necessary for overcoming the climate crisis (Wielopolski & Bulthuis, 2022).

Circular Economy is a promising concept that could address the challenges of the construction sector by creating a new, regenerative economic system and offering tools to address the environmental issues while promoting sustainable development (Bocken et al., 2016) (Rijkswaterstaat et al. 2022) (Ghisellini et al., 2016) (Mhatre et al., 2021), by creating resource loops to improve efficiency and limit waste (Bocken et al., 2016) (Ghisellini et al., 2016). Unfortunately, despite the promising nature of the concept, it remains underutilized. There are several factors that stand in the way of widespread adoption of CE principles in the industry.

First, the current frameworks have been mainly developed for products with a short to medium-length lifespan such as consumer goods due to which they lack the sufficient depth directly to be applied in construction projects which possess significantly longer lifespans. Besides longer lifespans, due to the inherent complexity of buildings, the construction industry requires in-depth, specialized solutions that the current CE frameworks are not able to provide. Thus, the current CE solutions are not sufficient to be utilized in the sector and, while certain aspects of CE principles can be seen in the industry, they are mainly tied to simple tasks such as byproducts not allowing for larger scale solutions (Minunno et al., 2018).

The surface level application of CE concept in the sector has had some unwanted effects, mainly resulting in the lack of clear definitions, standards, and research without a clear unified direction. These aspects have created an ambiguous environment around the topic of CE in construction, stalling the transition from the "business as usual" approach to a circular practice (Mhatre et al., 2021). (Eberhardt et al., 2020).

Finally, the construction industry lacks sufficient experience and "know-how" to operate all aspects that come with circular practice. As seen from the research of Brown (2021) most companies withing the industry are too unexperienced in the matters of circular operation, creating the loop of consequences where it is not possible to create circular buildings due to the lack of knowledge of the industry, and, in turn, it is not possible to train the practitioners due to the lack of circular projects.

In order to accelerate the transition towards a Circular Economy in the construction industry, it is necessary to redefine the concept of CE within the sector, unifying the fragmented research, and create strategies for ensuring a systematic transition away from the linear, "business as usual" way of operation.

1.4 Research objective

This research explores strategies for addressing the high environmental impact of the construction industry sector by focusing on the topic of circular economy. According to the research gap, the fragmented development of CE topic in the construction industry is one of the primary reasons of the limited adoption, thus pursuing this topic with a narrow focus in an attempt to specify the scope should be avoided. The research aims to explore the adoption of circular economy in the sector by taking a full lifecycle approach, including both the material use as well as the processes associated with the construction. It provides the preliminary steps for a strategy that can serve as a foundation for future research for achieving a comprehensive transition away from the linear "take-make-dispose" model of operation into a circular one.

The desired outcome is achieved by providing a comprehensive theoretical background about the construction industry, circular economy and their interrelations in a following sequence: 1. Providing a unified, clear definition of CE in the confines of the construction sector, 2. Mapping out stakeholders and their level of influence on the construction against enablers and barriers to highlight the actors that are in the best position to facilitate adoption of CE, 3. Identifying and analyzing both barriers and enablers to provide an exhaustive understanding of the factors influencing the adoption of circular practice in the sector, 4. Establishing connections between barriers enablers and stakeholders to find strengths that can be leveraged to overcome obstacles for the systematic adoption of CE, and 5. Establishing relationships between the findings to give a comprehensive overview of the variables in play for making the systematic transition of the industry possible.

The desired outcome is achieved through exploring the existing body of knowledge related to the topic of CE and construction. The findings of the report are presented in the form of preliminary strategies that use identified information about the barriers, enablers, stakeholders, and their relationships to find pathways for resolving the shortcomings of the CE in the construction industry.

1.5 Research question

The report aims to achieve the given research aim by answering the following Research Question (RQ):

> RQ: How can the construction industry accelerate the sector wide transition into a more circular way of operation using the principles of Circular Economy?

Given the time limitations of the research and the wide scope of the topic of CE the main RQ aims to outline only the most important, key limiting factors that get in the way of comprehensive adoption of CE in the construction industry and develop baseline strategies for addressing these limitations based on the available resources, strengths, and opportunities.

Furthermore, due to the complex nature of the construction industry and the CE, the main RQ is broken down into smaller Sub Questions (SQs) in an attempt to simplify the topic into specific more manageable portions. The SQs give a step-by-step approach to answering the main RQ by gaining a better understanding of the topics of Circular Economy, Construction Industry and its Stakeholders, and the factors that both enable and halt the adoption of CE principles in the sector. The findings from the SQs are later combined to answer the main RQ and avoid a fragmented approach to the CE which is frowned upon according to the preliminary research.

> SQ1: What does the Circular Economy entail in the context of the construction industry and how is the concept utilized in modern construction practice?

The preliminary research has made it clear that the construction industry lacks a clear definition of CE in the context of the sector, which has led to developments in many different areas without a clear unified direction. This has resulted in the dilution of the topic and halted its adaptation in the sector. This question will explore the history of CE, its origin, and its past application to understand the utility the concept can provide to the construction industry. Moreover, the SQ1 aims to provide a clear and concise definition of CE for the report to gain a clear understanding of the concept and make it easier to identify specific challenges that stand in the way of its adoption.

> SQ2: Who are the stakeholders involved in the construction industry and what power do they hold over adoption of a CE?

The construction sector has a large, complex supply chain and transitioning into a new way of operation will influence every actor. According to Banihashemi et al., (2024) CE should involve the entire supply chain for adequate results. With SQ2, the report aims to identify the stakeholders of construction practice and understand their involvement in construction, their power to make changes, and their motivations in an attempt to develop strategies of working with them. The answer will give an exhaustive overview of the most important construction actors, and the potential influence they have on adopting CE practice looking both at their power and interests. Exploring stakeholders will give more information about both barriers and enablers for the final framework, and a clear understanding of the actors allows the report to not only focus on the end goal but also develop strategies for interacting with the important entities that will eventually lead to the adoption of CE.

> SQ3: What are the most important barriers that limit the widespread adoption of CE practices in the construction sector that halt the industry wide transition?

After defining what Circular Economy entails in the context of the construction industry and providing an overview of the important actors, the report shifts its focus on defining the problems that need to be overcome by identifying the limiting factors that get in the way of adopting circular economy in practice. A clear understanding of a problem is essential for a well-defined solution. By answering SQ3 report aims to gain an understanding of the barriers that need to be overcome by the baseline strategy to accelerate the transition towards a circular practice.

> SQ4: What are the enablers that can enhance the widespread adoption of CE in the construction industry?

After identifying the main problems in the way of adoption of CE practice, research explores the strengths that can be utilized for solutions in the baseline strategies. SQ4 explores the concept of CE in the construction industry, looking into the successful circular construction projects and the CE frameworks to identify the enablers that allow for circular operation. Answering this question will give the research a full understanding of the strengths and opportunities that can be utilized by the construction sector to overcome the challenges in the way of circular operation and allow for development of comprehensive strategies that include all the available tools at hand.

> SQ5: What is the relationship between the barriers, enablers, and the actors of the construction industry and how can these connections be utilized to accelerate the industry wide transition?

Finally, after defining all the necessary background information about the strengths, weaknesses, and the actors, the research establishes connections between them to identify pathways that can be followed for overcoming barriers. Mapping out connections gives a unique perspective that shows what enablers can be leveraged, and by whom, for counteracting which barriers. This step combines the information from all the SQs to give arguments for answering the main RQ by developing a simple framework that can be utilized within the construction industry.

1.6 Thesis outline

The structure of the thesis is designed in a sequential manner, where the report begins with establishing the context for the research. Next, it defines and frames the problem before establishing the solution. Figure 2 shows the general structure of the report where the paper is split into 9 chapters of 1. Introduction, 2. Research methodology, 3. Definition, 4. Stakeholders 5. Barriers, 6.

Enablers, 7. Strategy development, 8. Discussion and limitations, and 9. Conclusion and recommendations.

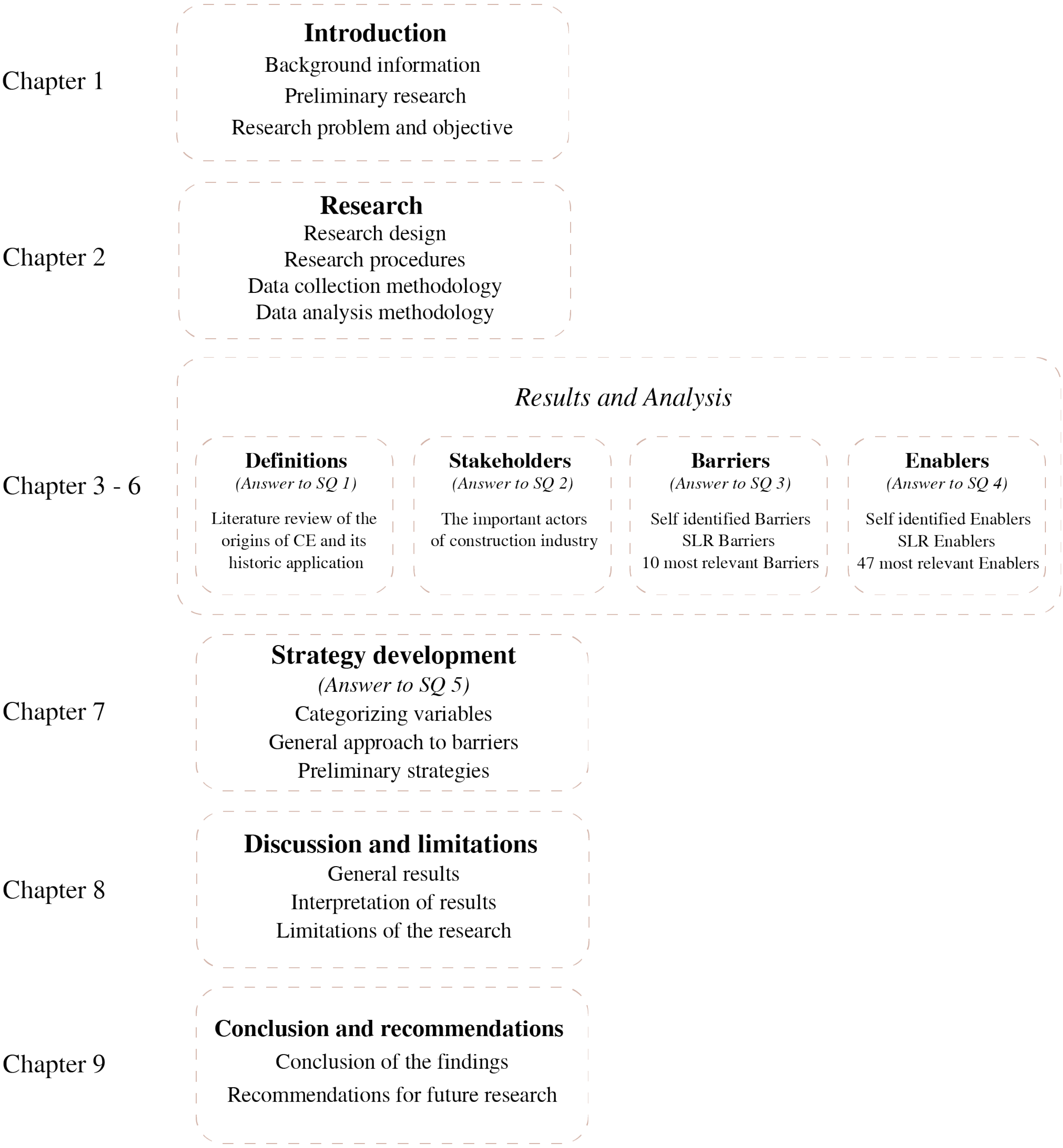


Figure 2 Thesis structure

Chapter 1 introduces the reader to the background information about the problems of the construction industry, the topic paper aims to address, and the scope of the research. This chapter establishes the context of CE in the construction industry and begins framing the issues associated with the use of CE in the sector.

Chapter 2 outlines the systematic approach the report takes for finding solutions. It introduces the chosen research methodology of Systematic Literature Review (SLR), elaborates on data gathering, selection, and analysis. The chapter also presents the frameworks used for synthesizing the data and provides a full overview of the research process to ensure transparency and allow for reproducibility of the findings.

Results and analysis are presented in the sequence of the SQs. First, SQ1 aims to frame circular economy by looking into its origins and past frameworks to find how it can be applied to the construction industry in chapter 3. SQ2 defines the context of construction industry looking into the important stakeholders, their roles and their power over the construction projects in chapter 4. Moving onto the SQ3, the paper identifies the main hurdles in the way of systematic implementation in order to give an exhaustive overview of the challenges that need to be overcome in chapter 5. After defining the main problems, the report moves onto identifying solutions by answering SQ4 and exploring the enablers of CE in chapter 6.

Chapter 7 utilizes the gathered data from the previous chapters to answer SQ5 by analyzing and synthesizing the findings in order to identify the connections between the explored topics and giving 10 barrier specific interventions as preliminary strategies.

Chapter 8 presents the interesting and important findings of the research and gives personal interpretations based on each of the findings. Additionally, it presents the main limitations of the research.

Finally, chapter 9 concludes the report providing the answer to the main RQ. Additionally, it provides recommendations for future research that can further contribute to the body of knowledge about the topic.

2. Methodology

This chapter provides an overview of the procedures followed throughout the research that were used to reach the answers for the RQ and SRQs. First, it introduces the research design while providing the rationale behind the chosen approach. It then discusses the RAMESES publication standards (Wong et al., 2013), which is the primary framework used to structure this paper. Following this, the chapter introduces a data collection methodology talking about the inclusion and exclusion criteria of the processed data. Finally, it dives into the methods used for analyzing the gathered data concluding with the data validation and limitations of this approach.

2.1 Research design

Due to the complexities and particularities of the problems the report aims to address, Systematic Literature Review (SLR) was chosen as the primary method of analysis. The topic as underdeveloped and fragmented as the CE in the construction industry, which lacks a clear direction and is limited in application, often results in conflicting viewpoints. A SLR allows for the combination of various kinds of data that can be complementary and conflicting giving an overarching narrative while eliminating certain amount of bias (Wong et al., 2013). Such a systematic approach can prove particularly relevant when defining the concept of a CE in the context of construction as well as while identifying enhancers and barriers of a CE that are specifically applicable to the construction industry. Additionally, a SLR serves as a foundation for new research by its transparent nature, allowing for reproducible research (Wong et al., 2013), which is particularly helpful in the context of this topic as the standardization of the definition of a CE is lacking.

With the research aiming to find strategies for systematic implementation of a CE in the construction industry, it is important to make all information available and easily accessible, allowing for further development and maturity of the topic in the sector. A SLR provides an ideal methodology to tackle these challenges.

2.2 RAMESES guidelines

After selecting SLR as the primary research methodology it is important to devise a strategy to transparently and clearly deliver the collected data through this report. RAMESES publication standards (Wong et al., 2013) were chosen as the main guideline for the delivery of this thesis. This framework simplifies the use of SLR and gives instructions on how to utilize the benefits of the chosen research methodology by conveying them in the report. RAMESES provides a list of 20 rules that need to be followed that can be seen in table 1.

Table 1. RAMESES publication standard (Wong et al., 2013)

Title	Description
1	Identify the document as a meta-narrative review or synthesis.
Abstract	
2	Contain the brief detail of the study's background, review question or objectives; search strategy; methods of selection, appraisal, analysis and synthesis of sources; main results; and implications for practice.
Introduction	
3 Rationale for review	Explain why the review is needed and what it is likely to contribute to existing understanding of the topic area.

4 Objectives and focus of review	State the objective(s) of the review and/or the review question(s). Define and provide a rationale for the focus of the review.
Methods	
5 Changes in the review process	Any changes made to the review process that was initially planned should be briefly described and justified.
6 Rationale for using meta-narrative review	Explain why meta-narrative review was considered the most appropriate method to use.
7 Evidence of adherence to guiding principles of meta-narrative review	Where appropriate show how each of the six guiding principles (pragmatism, pluralism, historicity, contestation, reflexivity and peer review) have been followed.
8 Scoping the literature	Describe and justify the initial process of exploratory scoping of literature.
9 Searching processes	While considering specific requirements of the journal or other publication outlet, state and provide a rationale for how the iterative searching was done. Provide details on all the sources accessed for information in the review. Where searching in electronic databases has taken place, the details should include (for example) name of database, search terms, dates of coverage and date last searched. If individuals familiar with the relevant literature and/or topic area were contacted, indicate how they were identified and selected.
10 Selection and appraisal of documents	Explain how judgements were made about including and excluding data from documents and justify these.
11 Data extraction	Describe and explain which data or information were extracted from the included documents and justify this selection.
12 Analysis and synthesis processes	Describe the analysis and synthesis processes in detail. This section should include information on the constructs analyzed and describe the analytic process.
Results	
13 Document flow diagram	Provide details on the number of documents assessed for eligibility and included in the review with reasons for exclusion at each stage as well as an indication of their source of origin (for example, from searching databases, reference lists and so on). You may consider using the example templates (which are likely to need modification to suit the data) that are provided.

14 Document characteristics	Provide information on the characteristics of the documents included in the review.
15 Main findings	Present the key findings with a specific focus on theory building and testing.
Discussion	
16 Summary of findings	Summarize the main findings, considering the review's objective(s), research question(s), focus and intended audience(s).
17 Strengths, limitations and future research	Discuss both the strengths of the review and its limitations. These should include (but need not be restricted to) (a) consideration of all the steps in the review process and (b) comment on the overall strength of evidence supporting the explanatory insights which emerged. The limitations identified may point to areas where further work is needed.
18 Comparison with existing literature	Where applicable, compare and contrast the review's findings with the existing literature (for example, other reviews) on the same topic.
19 Conclusion and Recommendations	List the main implications of the findings and place these in the context of other relevant literature. If appropriate, offer recommendations for policy and practice.
20 Funding	Provide details of funding source (if any) for the review, the role played by the funder (if any) and any conflicts of interests of the reviewers.

The research methodology, structure and the findings of this thesis will be given based on the given ruleset in order to stay consistent and present in a clear manner making it easier for the readers to understand both the process and the result.

With the use of a detailed publication standard such as RAMESES, this report aims to promote ethical and responsible research that can also be easily reproducible to allow follow-ups to the topic to build a cumulative body of knowledge about the complex problem tackled in this thesis. Additionally, as RAMESES was designed to improve the quality and clarity of the research (Wong et al., 2013) making it more actionable, the results of this research can provide a more palatable, founded arguments to a practical application, bridging the gap between academia and practice.

2.3 Data collection

This report has conducted research according to the RAMESES guidelines (Wong et al., 2013) which imposes strong principles for the conduction of data gathering. This chapter will discuss the procedures followed during the data gathering process starting from the selection of the scientific database, preliminary research, keyword selection, and inclusion/exclusion criteria. The total quantity of articles used in the report is equal to 59 papers.

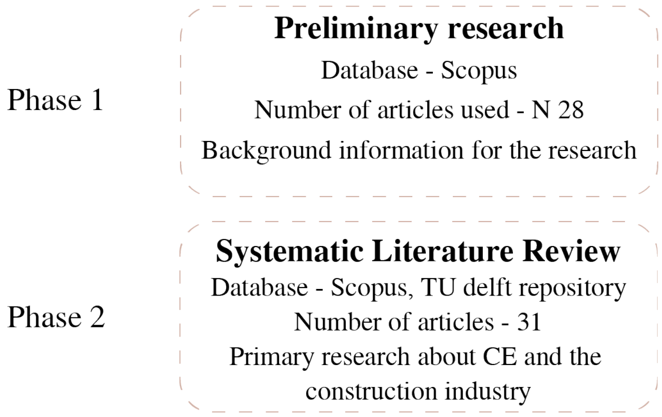


Figure 3. SLR data

Originally, the research was planned to be conducted in the combination of 2 databases, Scopus and Web of Science. Unfortunately, due to the complications with getting educational access to the database of Web of Science it was left out, making Scopus the primary database used in this report.

As can be seen in figure 3, there were 2 major phases for the research. Phase 1 included the preliminary research conducted before the start of the project to acquire relevant information for formulation of the research plan. During this phase, 28 articles were used to form the first chapters of the thesis. Phase 2 includes the main SLR, which was used to answer the RQ and SQs.

The process of data gathering and filtering during phase 2 can be seen in figure 4 which includes the keywords used in the research, number of articles found and exclusion criteria.

Data selection	Search query - ((TITLE-ABS-KEY ((construction OR "built environment" OR building) AND (circularity OR "circular economy" OR "circular development")))) AND ("construction management"), Database - Scopus, Number of identifier articles N - 600.
Initial screening	Data set limited to only open source articles in English language, Addition to the original search query - AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (OA , "all")) Number of articles after screening - N 326.
Secondary screening	Data set limited Based on the subject area (focus on the construction industry) and the location of the research (focus on research in the comparable construction industries to the Netherlands). Number of articles after Secondary Screening - N 152.
Full-text review	The selected articles were evaluated for eligibility in the following sequence: 1. Abstract review, 2. Introduction and conclusion review, 3. Full-text review. Number of articles after Full-text screening - N 81.
Final Dataset	Following the full-text review, due to the large quantity of the selected articles, a secondary full text review was conducted which eliminated redundant data while adding to the dataset through snowballing. The final number of articles for analysis was - N 31.

Figure 4. Phase 2 Data filtering process

Phase 1 research articles were used to refine the keywords for the phase 2 SLR. Various keywords found in the preliminary research were reviewed and refined for the next phase to optimize the analysis. The following keywords were used as the base for the paper: “construction”, “built environment”, “building, circularity”, “’circular economy”, “circular development”, and “construction management”. This selection yielded into the most complete dataset that was relevant to the construction sector while discussing the concepts of CE.

The SLR was concluded on 23rd of July 2024 with the following search query “*(construction OR "built environment" OR building) AND (circularity OR "circular economy" OR "circular development")))) AND ("construction management")*”and resulted in 600 articles. After limiting the results to open-source articles in English language this number went down to 326. Next step of screening eliminated articles from undesired subject areas such as, for example, agriculture, chemical industry, physics, etc. and resulted in selection of 152 articles. Finally, each article was analyzed based on the title, abstract and conclusion section, eliminating articles with an overly specific focus on materials or research conducted in too specific an environment to allow for wider application of the findings. The final search query can be seen in figure 5.

((TITLE-ABS-KEY ((construction OR "built environment" OR building) AND (circularity OR "circular economy" OR "circular development")))) AND ("construction management") AND (LIMIT-TO (OA , "all")) AND (EXCLUDE (SUBJAREA , "SOCI") OR EXCLUDE (SUBJAREA , "COMP") OR EXCLUDE (SUBJAREA , "EART") OR EXCLUDE (SUBJAREA , "PHYS") OR EXCLUDE (SUBJAREA , "CHEM") OR EXCLUDE (SUBJAREA , "CENG") OR EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "AGRI") OR EXCLUDE (SUBJAREA , "ECON") OR EXCLUDE (SUBJAREA , "MATH") OR EXCLUDE (SUBJAREA , "MEDI") OR EXCLUDE (SUBJAREA , "ARTS") OR EXCLUDE (SUBJAREA , "PHAR") OR EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "PSYC") OR EXCLUDE (SUBJAREA , "NEUR") OR EXCLUDE (SUBJAREA , "HEAL") OR EXCLUDE (SUBJAREA , "VETE") OR EXCLUDE (SUBJAREA , "NURS") OR EXCLUDE (SUBJAREA , "DENT")) AND (LIMIT-TO (LANGUAGE , "English")) AND (EXCLUDE (EXACTKEYWORD , "Compressive Strength") OR EXCLUDE (EXACTKEYWORD , "Gas Emissions") OR EXCLUDE (EXACTKEYWORD , "Aggregates") OR EXCLUDE (EXACTKEYWORD , "Reinforced Concrete") OR EXCLUDE (EXACTKEYWORD , "Cements") OR EXCLUDE (EXACTKEYWORD , "Thermal Conductivity") OR EXCLUDE (EXACTKEYWORD , "Geopolymer"))

Figure 5. Final search query

The full-text review of the articles has resulted in a dataset consisting of 81 articles, this step was repeated for the second time to get rid of redundant research on similar topics with similar conclusions while making limiting the quantity of the reviewed papers to a more manageable number. Similar articles were evaluated based on their number of citations, Scopus percentile, Scopus score and date. Additionally, 7 research papers were added to the dataset through snowballing method. An example of the dataset used during the filtering process can be seen in figure 6.

No limitation was set on the date of release of articles adhering to the principle of historicity from RAMESES guidelines. Despite this, all the articles in the final dataset of 81 were published recently, with the earliest publication being in 2017 showing the increasing significance of the CE in construction and a clear research gap in the field. Additionally, following the RAMESES principles of pragmatism, and pluralism, the research was not limited to only scientific articles to gather all the possible important data for the SLR. Figure 6 shows the example of the final part of the article screening process.

Article N	Name	Date	Scopus score	Scopus percentile	Citations	topic direction	Location	Original website	Keep
1	Circular design strategies and economic sustainability of construction projects in china: the mediating role of organizational culture	2024	NA	79	1	Organizational structure	China	10.1038/s41598-024-56452-0	Yes
2	Too good to waste: Examining circular economy opportunities, barriers, and indicators for sustainable construction and demolition waste management	2024	NA	NA	0	Barriers/Enhancers	UK	10.1016/j.spc.2024.05.026	Yes
3	An assessment of barriers to digital transformation in circular Construction: An application of stakeholder theory	2024	NA	NA	0	Stakeholders / barriers/Enhancers	NA	10.1016/j.asej.2024.102787	Yes
4	Reverse Logistics in the Construction Industry: Status Quo, Challenges and Opportunities	2024	NA	NA	0	Barriers/Enhancers	China/NA	10.3390/buildings14061850	Maybe
5	Evaluating the key competency skills of construction professionals for the attainment of circular construction in developing economies	2024	NA	NA	0	professional competences	Ghana	10.1016/j.clpl.2024.100060	No
6	Mega-Projects in Construction: Barriers in the Implementation of Circular Economy Concepts in the Kingdom of Saudi Arabia	2024	NA	NA	0	Barriers/Enhancers	Saudi Arabia	10.3390/buildings14051298	No

Figure 6. final screening

Besides the articles found from the Scopus database, the research included seven additional papers from snowballing method and 3 articles from the TU Delft repository. Due to the relative nuanced nature of the CE specifically in the construction industry the recent work from the TU Delft students can prove informative further reaffirming the principles of pragmatism and plurality.

2.4 Data analysis

Due to the immense amount of data alongside the complexity of the CE within construction industry, which, as previously mentioned, has led the concept to be developed in many different directions, it was necessary to approach the data analysis in a strategic manner. After the final screening of articles, each paper was analyzed by reading the full text. The information gathered from each paper was split into 5 different categories: definitions, enablers, barriers, stakeholders, and extra. Each category was designed with the intention of answering one of the SQs while the category "extra" included relevant information that could not be easily associated to one of the SQs. The documentation method was inspired by the process displayed in the thesis of Karlijn van Velzen (2023).

5 documents were created for each of the categories to combine the related data in a singular file. Important information from the articles was combined in these files with the additional comments and relevant references in a sequential manner that would follow the reasoning of the used in this thesis.

2.5 Validation

To make sure that the findings from this paper are realistic, it is necessary to validate the guidelines created by the paper. This displays one of the guiding principles of RAMESES, peer review. Originally, the validation session was planned to be done based on semi-structured interviews from the experts in the field in order to avoid and address the gap between academia and practice, which was one of the issues of CE in construction. Unfortunately, due to the limited responses from the desired participants combined with the time limitations it was not possible to conduct the interviews.

To bypass the issue of not having fresh data from the interviews, this thesis opted in validating the findings based on the transcribed interviews from the papers of the past students. The selected papers cover the topic of a CE or similar concepts in the built environment or adjacent areas thus mimicking the topic of this report.

Additionally, the sequential steps used for the research gave opportunities to drive conclusions from the available information about the following steps. For example, the gathered information from chapter 3 and 4 was used to identify barriers and enablers, which was later compared to the findings of SLR in the following chapters. While this method doesn't provide a full validity of the findings, the high correlation between the self-identified information and the data extracted from SLR hints at the reliability.

2.6 Use of AI tools

The report has utilized various tools to reach its final form, most notably, AI tools such as Chat GPT and NotebookLM from google were explored for assistance during data organization and writing process. It is necessary to disclose the utilized resources as well as the methods for the use of the said tools to maintain full transparency.

Chat GPT was used primarily for organizing thoughts, structuring ideas, and inspiration for writing. Throughout the thesis, when needed, this AI tool was given the summary of the ideas that need to be presented in a specific paragraph, and the output was further altered and used as an inspiration.

Googles NotebookLM was used in a more refined manner as it allowed for more opportunities for data refinement. This AI tool allows the user to give the predefined dataset that it uses to answer all the given questions. In the case of this report, NotebookLM was given the final dataset of the second phase of SLR. This tool was primarily utilized while writing chapters 3, 4, 5, and 6 as these parts used the largest number of articles and required further assistance for data organization. Using these tools the report aims to maintain consistency and quality by continuously backtracking on the findings.

2.7 Limitations

While great care was given while developing the methodology of this research it is important to recognize and state its limitations.

First, while a SLR is a strong research methodology that helps limiting biased research, it is not exempt from it. The research was conducted by a singular person over a short period of time. The selected articles, particularly during the last screening phase can display a selection bias.

Additionally, due to time limitations, a significant number of articles were excluded which opens the paper to the risk of overlooking relevant data.

Finally, the paper primarily focuses on scientific articles without gathering empirical research. This is particularly harmful for validating the findings. While the report attempts to bypass this issue by utilizing the data gathered from past students, this method is only a substitution and not sufficiently reliable.

3. Definition

According to the findings from the preliminary research presented in chapter 1, CE is a promising solution that has great potential for overcoming issues such as increasing demand for construction and high pollution faced by the construction industry. This is done by systematically reducing the CDW by promoting material recovery options and building deconstruction, improving resource efficiency through emphasizing recycling and reuse of building components/materials, and providing alternative cost saving options through, for example, secondary material markets (Bocken et al., 2016) (Rijkswaterstaat et al. 2022) (Ghisellini et al., 2016) (Mhatre et al., 2021), but, despite such potential, its adoption by the sector remains limited (Lee et al., 2023) (Minunno et al., 2018). Such limited adoption can be mainly attributed to the inadequacy of the current CE frameworks in dealing with the complexities of construction industry (Minunno et al., 2018) (Eberhardt et al., 2020), as well as the fragmented approach the sector has taken in researching the topic of CE (Eberhardt et al., 2020) (Adams et al., 2017).

The primary purpose of this chapter is to create a foundational understanding of CE and its application to the construction industry by answering SQ 1: *"What does the Circular Economy entail in the context of the construction industry and how is the concept utilized in modern construction practice?"*. The findings will serve as an essential reference point for the subsequent chapters as well as future research by providing a clear, refined definition of CE tailored to the construction industry as well as an overview of the current application of the concept in the sector.

The analysis is conducted in the following manner. First, the chapter looks to frame the Circular Economy by looking at its origins and development over time. This allows the paper to gain better understanding of the CE as a tool and view how it has been applied in the past and in what industries. This information can be used as a benchmark, allowing the paper to learn from the success of the sectors that were successful in adopting CE principles.

Following this, research shifts focus to the construction sector, by reviewing the ways it uses CE frameworks. It provides a comparison of the industries that have been successful in utilizing CE frameworks with the construction industry to identify the differences that limit the adoption. Additionally, paper presents the existing strategies used in the construction industry that allows for a more circular operation to show the state of the art that is used in practice. These findings give a baseline that shows the current state of the sector.

Next, the report aims to contextualize the CE in construction by mapping out its lifecycle and identifying the key areas of influence that will be impacted by the circular practices. These findings are used to develop strategies in the later stages of the report, by framing the construction practices and giving a comprehensive overview of the activities that can be influenced by adoption of CE.

Finally, the chapter is concluded by giving the overview of the main findings of this section which include a 1. Refined definition of CE for the construction industry, 2. A list of identified barriers that stand in the way of CE adoption, 3. Currently used circular strategies in the sector, and 4. Critical areas influenced by the CE frameworks and the lifecycle overview of the construction projects.

3.1 History of CE

The Circular Economy is one of the finest instruments that addresses society's needs of long-term development and economic growth (Ghufran et al., 2022). It is perceived as a method that allows for integrating societal, economic, and environmental values for maximizing product value by stepping away from the linear economies and transitioning into circular ones (Ghufran et al., 2022).

While it's current state of definition is new, the concept has roots going back to the 1960s (Geissdoerfer et al., 2017) from the work of Kenneth E. Boulding who described the Earth as a "closed circular system with a limited assimilative capacity". While this paper focuses on CE primarily in the construction industry, it is useful to look at the past to understand the core principles of the topic.

Following Boulding's work, the CE started taking shape in late 1970s with the origins often attributed to David Pearce and R. Kerry Turner who explored the linear and open-ended characteristics of contemporary economic systems by describing the influence of natural resources on economy as both inputs and outputs (Geissdoerfer et al., 2017). Over time, the definition and understanding of CE expanded emphasizing the importance of resource regeneration and loop thinking. Some of the most influential frameworks being Cradle-to-Cradle, Laws of Ecology, Looped and Performance Economy, Regenerative Design, Industrial Ecology, Biomimicry, and the Blue Economy, mostly developed for industrial and manufacturing industries (Geissdoerfer et al., 2017). These industries were ideal targets for adoption of CE frameworks due to their centralized operations, standardized material and manufacturing processes, which put them in a great spot for implementing loop thinking in their processes.

Since then, CE has become increasingly popular in various industries on a global scale which can be seen reflected in international policies. Germany was a pioneer who has integrated CE in its laws as early as 1996 (Geissdoerfer et al., 2017). This precedent was followed by Japan in 2002 with the introduction of "Basic Law for Establishing a Recycling-Based Society", China in 2009 "Circular Economy Promotion Law of the People's Republic of China", and the EUs 2015 Circular Economy Strategy (Geissdoerfer et al., 2017).

The research makes it clear that Circular Economy is seeing increasingly strong interest from policymakers and governments, showing the great potential it has as a tool for addressing the problems faced by the modern world. But, despite its benefits, it is not a tool that can be utilized in every scenario, which is evident by the lack of its widespread adoption in the current day. Historically, CE has thrived in the sectors producing consumer goods, such as manufacturing. While this might be attributed to a coincidence, there are several reasons to why the concept has thrived in these industries: 1. These sectors have operated in a highly standardized environments mainly with the materials and processes which gave opportunities for reproducible and highly controlled interventions that increased efficiency of production and allowed for recycling and resource recovery, 2. These industries were prone to have centralized operations and supply chain, which facilitated increased communication and interactions in a controlled environment. Such practice allowed for a comprehensive implementation of CE principles instead of a fragmented approach. These factors created an environment that has allowed for a successful implementation of CE in the past and can be used as a benchmark for the construction industry to strive for.

3.2 General definition

CE development and research in the construction sector has long lacked unified direction, often chasing solutions in isolated, fragmented manner (Eberhardt et al., 2020) (Adams et al., 2017). Without a clear understanding of the topic, it is difficult to develop tangible solutions, thus it is necessary to frame what CE entails in the construction industry before seeking solutions for its adoption.

Over the years CE has had various definitions, but its general goal of minimizing the waste and maximizing the value of resources by keeping them in a continuous production loop has remained unchanged (Adams et al., 2017) (AlJaber et al., 2023). These goals have been generally achieved by creating a restorative and regenerative economic system in which resource use and waste production are minimized by narrowing (efficient resource use), slowing (temporally extended use) and closing (cycling) material loops (Eberhardt et al., 2020) (Brown et al., 2021).

Banihashemi et al. (2024) has identified 3 basic principles that accommodate the CE practice: first, the waste is designed out of the system, which forces the industry to design products with the purpose of disassembly, adaptation, and reuse in mind. Second, the CE focuses on people as users instead of consumers, by designing more durable and less perishable products. This approach ensures that at the end of the products' lifecycle it becomes a material for future products. Finally, CE prioritizes sustainable energy sources to be used for production of the products in the economy (Banihashemi et al., 2024) (Zvirgzdins et al., 2019) (Ghufran et al., 2022) (Geissdoerfer et al., 2017). These principles have been further developed into frameworks such as 6R principles (Reduce, Reuse, Recycle, Recover, Redesign, and Remanufacture), the 9R principles (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover), and can also be sees in international frameworks such as EU waste hierarchy see figure 7 (Lee et al., 2023). As shown by figure 7 the opportunities for circularity increase or are at higher level with the implementation of preventive actions.

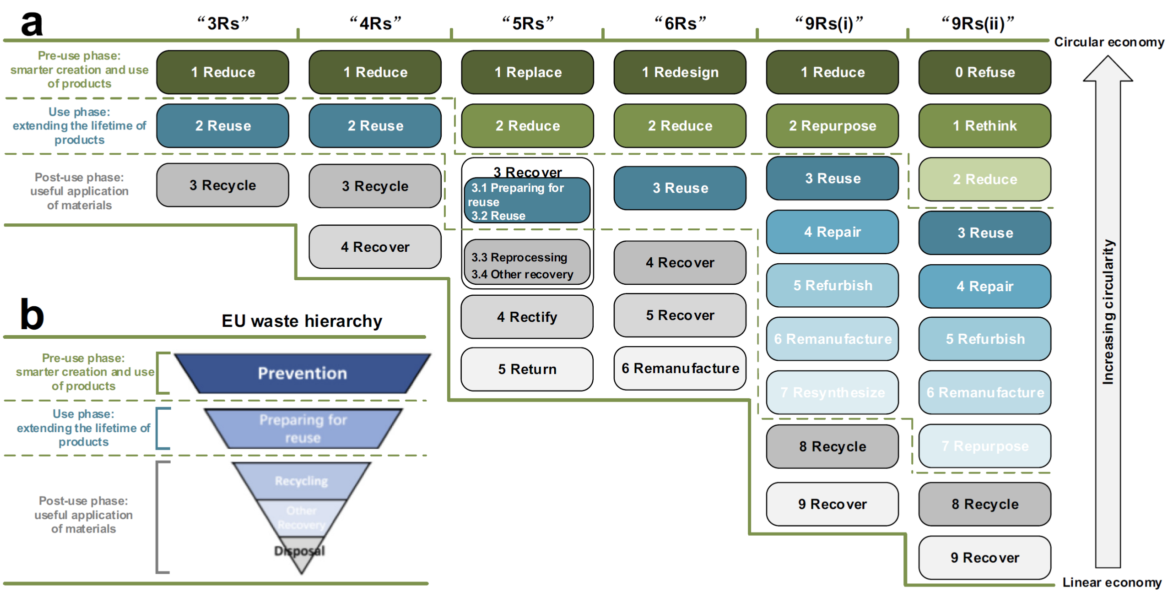


Figure 7. comparison of CE and waste hierarchy (Zhang et al., 2021).

Sustainability was a recurring topic during the research that was often compared with CE. While it is not unusual to see academic papers to draw comparisons between the two due to the similarities, it was surprising to see that these comparisons, sometimes, went as far as authors using the two concepts interchangeably, or utilizing the three pillars of sustainability to evaluate circularity (Adams et al., 2017). This tendency was seen both in the reviewed academic papers and in all the repository articles which further shows the problematic nature of the lack of an accepted CE definition. The most notable findings can be seen in well-established articles of Pomponi & Moncaster (2017), that put great focus on societal benefits while discussing circular projects when this is specifically a goal of sustainable development. This is concerning as such diffusion of topics in well trusted academic articles reflects on the newer research such as, for example, in the works of Aboutalebi (2023) or Baldew (2023) from TU Delft repository, where both papers aim to focus on Circular Economy but evaluate their respective projects based on sustainability criteria.

As suggested by Adams et al. (2017) Establishing a conceptual relationship between the two is helpful for avoiding diffusion of either topic. This can be done by exploring similarities and differences to gain a better understanding of what distinguishes CE from sustainability.

Geissdoerfer et al. (2017) implies that CE is a practical tool that can help accomplish sustainability related goals to a limited extent. This relationship stems from both concepts sharing similar goals and motivations, for example, both concepts strive for resolving environmental and economic challenges in the world, but their approach varies significantly. Sustainability has open-ended goals that aim to equally benefit all its 3 pillars of ecology, economy, and society. Moreover, it puts a focus on maintaining the sustainable state of the world over an indefinite period of time which is drastically different from CE approach (Geissdoerfer et al., 2017).

The Circular Economy approach, unlike sustainability, is based on a simple observation that resources can be used more efficiently, while waste and pollution can be reduced in a circular rather than linear systems (Geissdoerfer et al., 2017). It possesses a much more defined objective of optimizing resource loops and eliminating waste. This objective has a clear end-goal as there is always a limit for optimization of systems unlike the objective of sustainability. Additionally, while there are some similarities between the areas of focus between CE and sustainability, Circular Economy priorities environmental and economic benefits with the benefits to the society coming only as a byproduct. This fundamentally differentiates the two concepts and shows that the goals of CE should not be diffused with sustainability. A more detailed comparison between CE and sustainability can be viewed in the tables presented in Appendix A. Such misrepresentation and dilution of the concept can act as a barrier in the way of its adoption in the construction industry.

Keeping the specific goals of CE and its practical approaches for achieving the said objectives in mind, the most well accepted and refined definitions of the topic in modern day are as follows: "*an industrial economy that is restorative or regenerative by intention and design*" given by the Ellen MacArthur Foundation (2022), and *"An economy that preserves the value added to the products for as long as possible and virtually eliminates waste. The resources are retained within the economy when a product has reached the end of its life, so that they remain in productiveuse and create further value"* by the European Commission (AlJaber et al., 2023). The latter is the most complete version of a general CE definition found during the SLR and is used as a starting point for finding a construction industry specific definition of Circular Economy.

3.3 CE and the construction industry

The circular economy, at first glance, provides the construction industry with new opportunities of dealing with the increasing demands in an environmentally conscious manner by reducing the need for raw materials, limiting waste generation, and minimizing pollution. Unfortunately, the research gap has shown that despite its successes in Industrial and manufacturing sectors, the current frameworks fail to adapt to the inherent complexities of the construction industry.

This chapter provides a thorough overview of the use of CE in the construction industry by synthesizing the data gathered during SLR. It investigates the construction sector to identify its unique characteristics and compares it to the industrial or manufacturing sectors, that have been successful in implementation of CE, to pinpoint the differences that could be acting as barriers to the systematic transition. It is important to note that while the SLR was conducted with the emphasis on the construction sector and focusing on the CE based on these limitations, the articles providing with the definition of the concept were incredibly limited, further emphasizing the need for a comprehensive definition.

First, it is useful to know how academic literature defines CE in the construction industry to gain a basic understanding of the circular approaches in the sector. Gerding et al. (2021) describes circular construction as a “life cycle approach that optimizes buildings’ useful lifetime, integrating end-of-life phase in the design and using new ownership models where materials are only temporarily stored in the building that acts as a material bank”. This definition is further extended by Shooshtarian et al. (2022) who also stresses about the importance of waste minimization from the design stage and longevity of constructions but additionally emphasizes the importance of making constructions more easily repairable, upgradable, and usable in different ways. The most complete description found from the SLR is as follows “a building that is developed, used, and reused without unnecessary resource depletion, environmental pollution and ecosystem degradation. It is considered in an economically responsible way and contributes to the well-being of people and the biosphere. Here and there, now and later. Technical elements are demountable and reusable, and biological elements can also be brought back into the biological cycle” (AlJaber et al., 2023). The given definitions show clear similarities to the traditional CE frameworks, touching upon the important themes such as resource efficiency and reusability, environmental and economic responsibility, and temporal considerations. Moreover, they introduce several important concepts such as necessity for a lifecycle approach, the value of interventions at the design stage, new ownership models, and necessity for multiuse designs. Unfortunately, these descriptions have some limitations, mainly while they provide a great general overview, they lack the nuances to make them applicable for specific cases. Moreover, they include the goals that are more in line with sustainable development, for example “contributes to the well-being of people and the biosphere” is a clearly a societal pillar of sustainability and, while it is nice to achieve in projects, this diffuses the goals of CE making them more confusing.

To reach a more applicable definition, the report explores the construction industry, the way it utilizes CE strategies in practice, and provides a comparative analysis of various sectors. This information allows the paper to present the current state of CE in the construction industry, the issues with the current approaches, and potential areas that pose as barriers for CE adoption.

3.3.1 Characteristics of the construction industry

The paper has stated several times that the complex nature of the construction industry is one of the primary barriers in the way of adoption of CE frameworks, as these tools are insufficient in dealing with many aspects of construction practice. This section will explore and define these complexities to create a better understanding of a construction sector and identify how it differs from industries successfully in utilizing CE.

According to Nikolić & Cerić (2022), the construction industry can be considered to be dealing with some of the most complex ventures across all industries. They tie such complexity to the following reasons: 1. Its approach is unique and project-based, which significantly limits standardization opportunities, 2. It possesses a high level of fragmentation, both in its supply chain and processes, 3. It works on large-scale projects that have long lifespans, which brings uncertainties both during construction and operation phases (Nikolić & Cerić, 2022) (Lafhaj et al., 2024).

The project-based approaches are one of the most defining factors of the construction industry. Every new project is unique and varies in design, required delivery times, costs, and material requirements. This characteristic is unavoidable even when replicating the same designs, as despite the identical scope, environmental conditions such as location of the project make each new venture unique and results in lack of consistency and replicability of the processes (Nikolić & Cerić, 2022). In comparison, the previous findings show that the industries that were historically successful in utilization of Circular Economy principles focused on the production of simple products that were produced in a highly controlled environment that allowed for standardized operations and ensured reproducibility of the results (Lafhaj et al., 2024) (Nikolić & Cerić, 2022) (Pomponi & Moncaster, 2017).

The supply chain is an additional variable that increases the complexity of the construction industry. The sector deals with a fragmented supply chain, with many stakeholders each with unique visions, goals, and interests (Lafhaj et al., 2024). The large quantity of the stakeholders makes it difficult to maintain optimal level of collaboration and information exchange. Lack of timely, high-quality information resulting from the complicated supply chain of construction industry, makes collaboration and decision making difficult, which, in turn, reduces the quality of the deliverables and increases the required time for delivery. Using the previous findings from chapter 3.1 it is possible to make a comparison and say that, unlike the construction sector, the industries that have historically succeeded in utilizing CE principles, have mainly operated within controlled environments and centralized supply chains that have facilitated information exchange, making collaboration and alignment of interests easy and creating an ideal environment for circular operation (Pomponi & Moncaster, 2017).

Additionally, the construction industry works on large-scale projects that require high amounts of financial and material resources. The structures are composed of a wide range of high-quality materials such as concrete, steel, timber, etc., with each having different lifespans and maintenance requirements (Pomponi & Moncaster, 2017) (Eberhardt et al., 2020). Moreover, the products developed in the construction industry have a long lifespan, both during construction and operation. The construction processes often last for several years depending on the size of the project, while the buildings are designed for operation for up to a century (Pomponi & Moncaster, 2017) (Nikolić & Cerić, 2022). The long-lasting nature of the construction projects leave them susceptible to the influence of environmental factors outside the scope of the traditional project management, while making it difficult for the used building materials to be reliable for recycling purposes in a circular practice. These issues are very unique and inseparable from the construction industry which makes it difficult to follow in the footsteps of industrial or manufacturing sectors that deal with short lived products that are produced with uniform materials and can be optimized for reproduction (Minunno et al., 2018) (Lee et al., 2023) (Eberhardt et al., 2020) (Pomponi & Moncaster, 2017).

Finally, the construction industry is renowned for its traditional, risk averse nature. In practice, the construction practitioners are hesitant to adopt innovative practices due to the high upfront costs and the financial risks associated with such actions. Additionally, regulatory frameworks for the sector prioritize safety over efficiency, often requiring overdesigned structures to meet the safety requirements, but there is a lack of clear incentives for adopting CE practices (Pomponi & Moncaster, 2017). The limited incentives tied with the high safety regulations limit the options for circular operations. Particularly, there are no standardized approaches for reuse of construction materials, especially for structural applications. It's not possible to follow the example of the manufacturing and industrial industries for incentivizing change, as the regulatory constraints and lack of technological developments for material reuse make it nearly impossible to close the loops of materials (Lee et al., 2023) (Eberhardt et al., 2020) (Pomponi & Moncaster, 2017).

Table 2 summarizes the findings of this chapter by combining the findings and giving a concise visual overview of the differences between the industries that make it difficult to adopt the solutions from one to another despite their clear success in the past. These findings give an interesting baseline for exploring the barriers of CE in construction as it shows the inherent characteristics of the sector that get in the way of adopting the concept.

Table 2. Differences between the operation of construction industry and the manufacturing and industrial sectors

Aspect	Manufacturing and industrial sectors	Construction industry
Lifecycle	Short/medium-lived consumer goods designed for multiple refurbishments.	Long lived products lasting several decades.
Scale	Small to medium scale products, such as electronics, textiles, automobiles etc..	Large scale products, such as bridges, buildings, monuments, etc.
Materials	Small scale use of simple metals and plastics with relatively low quantities.	Utilizes high grade metals, concrete, and timber in high quantities.
Design approach	Products designed for easy repair and refurbishment.	Structures designed for longevity.
End-of-life strategy	Refurbishment, recycling, or remanufacturing.	Demolition/Deconstruction/ Recycling
Supply chain complexity	Centralized production with limited stakeholders.	Complex, fragmented multi stakeholder system

Focus on resource efficiency	Focus on efficient production.	Lifecycle approach with efficient production, use, and reuse.

It has been stated several times that Circular Economy poses great potential for aiding the construction industry in keeping up with the housing demand while dealing with the polluting nature of the sector. It is clear that the industry lacks behind in the adoption of this concept in its practice and could greatly benefit from learning from the other sectors that have succeeded in utilization of CE principles. Chapter 3.1 of the report has given an overview of the factors that have contributed to the success of CE in the manufacturing and industrial sectors, but it is necessary to recognize and understand the differences between the industries in order to successfully implement solutions from the past. This chapter has given an overview of the most important differences that make the implementation of the said solutions difficult. The main findings show that, compared to the traditional sectors which have a high maturity of CE, such as the manufacturing and industrial sectors, the construction industry produces a more complex, long-lived, large-scale products, that require use of large quantities of components and high-quality materials, each with varying costs, lifecycles, functions, and characteristics(Lee et al., 2023) (Eberhardt et al., 2020) (Pomponi & Moncaster, 2017). Additionally, due to the unique, project-based approach of the industry, it is difficult to develop singular solutions that can apply to every project as each case possesses unique challenges. Finally, the industry is risk averse and lacks clear incentives to alter its processes, while having to comply with the strict safety regulations that limit opportunities for material reuse and recycling. These differences create challenges that are unique to industry and, while it is useful to investigate other practices for solutions, they cannot be resolved by simply mimicking other sectors as they require deeper understanding of both CE and the construction industry.

3.3.2 The state of the art in the construction industry

The previous chapter has given an overview of the general characteristics of the construction industry that differentiate it from the sectors that have successfully applied the principles of CE to their operation. Primarily, these differences stem from the large scale of the construction projects, long lifespans, and the project-based approach taken by the industry for production. These factors create a unique environment that requires a different approach to implementation of CE. Before devising specific strategies, it is necessary to better understand the construction industry and its state-of-the-art with regards to circular mode of operation. This chapter explores the commonly applied strategies in the industry that influence the circularity of the processes in an attempt to gain a clear overview of the maturity level of CE in construction. By examining the said strategies, the paper gains insights about the construction sector and identifies potential enablers that can facilitate a systematic transition to circularity.

A general trend can be seen where majority of the activities focus on development of long-lasting designs, optimizing maintenance works such as repairs and monitoring, promoting reuse of materials and services, remanufacturing building components, refurbishing constructions, and recycling. This is supported by Zvirgzdins et al. (2019) who also suggests that these strategies all require lifecycle approaches. According to Lee et al. (2023) the CE strategies in the construction industry can be split in the following six categories: design for disassembly, building materiality, construction processes, building operation, building optimization, and end-of-life (EOL) strategies. The following paragraphs will summarize the findings of SLR showing various identified strategies that are in use in the sector from the findings of the following authors (Adams et al., 2017) (Lee et al., 2023) (Zhang et al., 2022) (Eberhardt et al., 2020) (Shooshtarian et al., 2022) (Kanters, 2020) (Elghaish et al., 2023) (Barbhuiya & Das, 2023).

Design for Disassembly (DFD) is an approach that includes the considerations of construction projects EOL activities at an early stage. The main approach for the strategies in this category focus on simplifying deconstruction and recycling of high-value materials at the EOL of projects, which allows to reduce waste and preserve the value of building materials. The following are some of the methods that have been identified during SLR that follow the principles of DFD: design for dismantling, design for deconstruction, design for recycling, design for adaptability, design for flexibility, and designing out waste.

Building materiality strategies focus on the selection and use of building materials. Some of the activities in the construction sector with regards to this category are as follows: The use of high-strength materials to increase the quality of the deliverables and extend the lifecycle, use of secondary materials such as recycled concrete or reclaimed timber to reduce the use of virgin materials, use of bio-based materials, and selecting less hazardous materials to minimize environmental and health impacts. It is important to note that, while the construction industry does use secondary materials where applicable, this precedent is limited as the sector has to comply with the strict safety regulations and the currently available technologies do not allow for proper evaluation of the quality of recycled materials limiting opportunities for reuse. Moreover, SLR has shown that one of the less implemented but potentially influential strategies is the use of material passports and creation of material banks that would simplify identification and reuse of appropriate materials in the industry (Lee et al., 2023) (Zhang et al., 2022).

SLR has identified various activities related to the construction processes that influence circularity of construction projects. These activities mainly focus on increased efficiency and standardization of processes as well as better information management. Modular construction and prefabricated designs are examples of strategies that increase circularity of projects by facilitating more precise, controlled and standardized processes for constructions which result in reduced material use and waste generation. Additionally, digital technologies like BIM and blockchain provide the tools to better track the projects with the improvements in transparency, monitoring, and availability of information. Moreover, Life Cycle Assessment (LCA) models allow for better quantification and evaluation of components simplifying decision-making processes and providing valuable information for communication between stakeholders. Finally, the use of shared building equipment strategies further reduces the generated waste and need for raw virgin materials.

Building operation and optimization strategies focus on extending the lifecycle of construction projects by smart design, maintenance and use activities. At earlier stages of construction, development of adaptable and flexible designs gives opportunities for reuse of structures without the necessity to conduct additional building activities. The products as service ownership models are becoming increasingly relevant as they allow for better risk allocation and distribution, putting the most capable actors in primary position to deal with them. The previously mentioned tools of

BIM and blockchain provide further opportunities for optimizing use of space and maintenance during operation by monitoring and providing high quality data.

Finally, EOL strategies include activities such as selective demolition, smart dismantling, recycling, reverse logistics, and urban mining. These techniques ensure the recovery of valuable materials and allow for closing the resource loop, minimizing waste and pollution, and ensuring the integration of high-quality materials back into new construction projects. Table 3 provides a general checklist of the activities while dealing with the common construction materials at the EOL stage and recommended activities to enhance circularity based on the EU waste hierarchy framework (Zhang et al., 2022).

Table 3. End-of-Life phase activities for construction demolition waste based on EU waste hierarchy framework (Zhang et al., 2022).

	Concrete and other stony waste	Metal	Wood	Glass	Plastic	Insulation
Preparing for reuse	prefabricated concrete products and elements (walls, floors, stairs, floors, etc.) may be reused	(i) steel-section element could be reused; (ii) whole portal frame buildings can be reclaimed for reuse	dimensional timbers, chipboards, timber doors, windows, and floorboards could be reused	glass panes and panels could be reused	plastic pipes and claddings could be reused	insulation layer in building elements could be reused
Recycling	processed as feedstock in new concrete production	re-melted to produce new ferrous products	recycled as feedstock in new wooden products	recycled as feedstock for new vitreous products	processed as a feedstock for producing new plastic products	recycled for producing new insulation
Other recovery	downcycled for other applications instead of making new concrete	No recovery options for steel.	(i) energy recovery; (ii) chipped as an organic mulch in gardening, landscaping, (iii) compost	(i) crushed for backfilling; (ii) ground and refined as feedstock for making concrete and aerogel	energy recovery	(i) energy recovery (ii) processed as additives for producing concrete
Disposal	should always be avoided	should never be considered	should always be avoided	should always be avoided	should not be considered	should always be avoided

These are the identified strategies that are seen most often in the current construction industry, but their appearance in academic literature does not paint a whole picture. According to Adams et al. (2017) lots of the CE strategies in the sector are applied in isolation with one off project and seldom see a widescale adoption. To provide a most complete overview, the report presents the most commonly used and most influential strategies that were discovered in the analysis.

According to Eberhardt et al. (2020), Assembly/Disassembly, material selection/substitution, adaptability/flexibility, modularity, and prefabrication and the most used strategies identified in the literature. This data can be further supported from the findings of Gamage et al. (2024) which identified that the strategies under the DFD category in this paper appear most often in the literature, followed by effective waste management, use of secondary materials, reduction of construction waste, and prefabrication. Use of BIM can be added to this list based on the research from Lee et al. (2023). Many of the strategies identified in this research are not commonly utilized in academia or the construction industry on a larger scale due to the limited interest in the circular construction, financial burden, and lack of incentives for operating in such a manner, but they should not be overlooked as they could provide opportunities for future solutions. While there are no singular breakthroughs that could resolve all of the issues, each solution is relevant as they could address specific problems/barriers to improve the perception of CE in construction and accelerate transition.

3.4 Lifecycle of construction projects

The primary aim of the paper is to identify strategies for systematic transition of the construction industry from linear to circular mode of operation. As stated in chapter 1, this requires a comprehensive approach across the entire lifecycle of the projects, but several inherent characteristics of the construction industry make it difficult to achieve this. The issues stem primarily from: "the complex, fragmented supply chain of the sector where each stakeholder is self-interested and lack the ability to make necessary decisions for comprehensive transition" as well as "the long timeframes of the construction projects which increase the uncertainties and opportunities for errors to occur". This chapter addresses the latter to gain insights about the factors that come in play due to the long lifecycles of construction projects.

Inherently long timeframes of the construction projects and buildings is one of the primary differentiating characteristics of the sector identified in chapter 3.3.1. This creates a unique environment for applications of CE as the concept has mostly been applied for sectors focusing on medium to short-lifespan products such as consumer goods (Pomponi & Moncaster, 2017) (Eberhardt et al., 2020). The long lifespan of the projects creates more opportunities for errors during production, operation, and EOL. Additionally, it elongates the use of the materials in the loops, leading to further deterioration, loss of value, uncertainty, and generally increases the complexity for circular operation. To tackle these issues, it is necessary to gain a better understanding of the complex lifecycle of the construction projects and simplify it by splitting it into smaller, more manageable portions looking at general patters and steps for progression. This chapter analyzes the various phases of construction projects, gives an overview of the general activities that take place during each phase, and attempts to connect these phases to the CE strategies presented in chapter 3.3.2 based on own interpretation according to the presented information.

The construction procedure usually follows a set of successive phases each with distinct activities and tasks. Each phase presents unique opportunities for implementation of CE principles such as waste reduction or optimization and understanding of these phases gives opportunities for implementing targeted solutions to maximize the benefits of CE. Table 4 presents the combined findings from 3 different authors about the phasing of construction projects. Lee et al. (2023) gives a most comprehensive overview of various perspectives of construction phasing by systematically analyzing the previous findings about the topic and presenting three different variations for the phasing each applicable to the specific scenario. In general, all papers follow the similar process starting with Design, the only outlier being Van Velzen (2023) which starts earlier at the initiation phase considering the processes before the decisions is made to make a new construction, including strategic objectives of the project, as well as determining its feasibility. The design stage develops the technical, functional, and aesthetic aspects of the project by creating architectural, structural, and engineering designs. Shooshtarian et al. (2022) notes that while following a circular approach it is necessary to incorporate as many strategies as possible during design phase as it dictates all the later phases and gives the highest degree of freedom for making changes (Gerding et al., 2021) (Lee et al., 2023). This notion is in line with the generally accepted progression of construction projects from Dewulf (2013) which suggests that the early stages of construction allow for the highest influence over the future of the projects and decisions at this stage generally require the least amount of costs.

Table 4. phases of construction according to literature.

(Ding et al., 2023)	(Lee et al., 2023)	(Lee et al., 2023)	(Lee et al., 2023)	(Van Velzen, 2023)
Design	Design for disassembly	Design	Design	Initiation
	Design for recycling			Planning
	Materiality			
Manufacturing			Manufacturing and supply	
Construction	Construction	Construction	Construction	
Operation	Operation	Use	Use and refurbishment	Operation
	Optimization			Maintenance
Deconstruction	End of life	End of life	End of life	
Product reuse				
Waste distribution				
Material reprocessing				

The next step addresses the supply chain of construction with manufacturing and supply phase, it usually contains the production, transportation, and storage of building materials and components. Using the information from the previous chapter it is possible to match specific strategies to this phase, mainly the following strategies can be interpreted to be applicable: selecting building materials with lower embodied energy (EE), prefabrication of building components for increased efficiency, supply chain and logistics management to ensure just in time delivery of construction materials with efficient supply routes, and optimal storage and handling of building materials to ensure good quality (Lee et al., 2023).

The construction phase is the next step, and it includes all activities starting from site preparation to finalizing the building. This phase presents the opportunities to use CE strategies such as: efficient material use, on site waste minimization, green construction logistics, and efficient use of resources such as heavy machinery, scaffolding or formwork (Lee et al., 2023).

Next, buildings enter the use phase which combines operation, maintenance, and refurbishment. During this period, while attempting to incorporate CE principles, it is efficient to focus on extending and narrowing the material loops by ensuring optimal performance of the building with proper maintenance procedures and respectful use. Strategies in the optimizing and operation categories in chapter 3.3.2 offer optimal solutions for this stage of construction.

Finally, the last phase of the construction projects is end of life (EOL), which focuses on the activities such as deconstruction, demolition, and management of the resulting materials. According to Ding et al. (2023) in a circular construction, this phase should be further split into reduction, reuse or recycling, but, while interesting, this was the only time this requirement appeared during SLR mainly because EOL already includes the suggested activities. Some of the CE strategies applicable to this stage include selective demolition, smart dismantling, recycling, reverse logistics, and urban mining.

In conclusion, construction projects generally follow similar chronological sequence of phases based on the literature review. However, slight variation does appear in certain articles depending on the context and focus of the research, for example how where researchers interested in the early stages of construction split the design phase into smaller segments, while EOL researchers focus on specific activities taking place at the opposite end of buildings lifecycle. All the articles found in SLR follow the same general sequence with only slight alterations to the level of detail in the case of Van Velzen (2023) who split the design phase in initiation and planning due to the general focus on the early activities, and Ding et al. (2023) who suggests a more detailed differentiation of EOL phase as the said research explored the flow of materials focusing on Forward and Reverse logistics. Synthesizing the findings, the paper identifies the following 5 phases:

- Design
- Manufacturing and supply
- Construction
- Operation
- End of life (EOL)

Each of the given phases conducts specific activities and presents unique opportunities for implementing CE strategies, some of which have been shown in the chapter. A systematic transition to circular mode of operation necessitates the industry to implement targeted strategies at each stage of the lifecycle of the project. The chapter gives a concise list of general phases of the construction industry and their basic characteristics. This information is essential for developing an overarching approach for circular construction industry where solutions at each phase work in unison to optimize the system and create efficient loops to maximize environmental and economic benefits.

3.5 The influence of CE on construction

A circular economy presents a complex, new way of operation that requires the construction industry to shift away from the traditional linear practices and, as mentioned before, the success of this transition relies heavily on making a comprehensive commitment to change. Overcoming this complex challenge requires a joint venture between the highly diverse actors of the construction industry (Owojori & Okoro, 2022) to create nuanced solutions (Wielopolski & Bulthuis, 2022) (Zvirgzdins et al., 2019). This chapter explores the way in which construction sector is influenced by CE frameworks underlying the specific areas of influence.

SLR has identified three academic articles that attempt to identify the key dimensions of influence of CE frameworks. These findings can be viewed in table 5.

Table 5. Dimensions of CE according to various authors

(Pomponi & Moncaster, 2017)	(Alhawamdeh et al., 2024)	(Gasparri et al., 2023)
Governmental	Political	Governmental
Economic	Economic	Economic
Environmental	Social	Environmental
Behavioral	Technological	Methodological
Societal		Sectoral
Technological		Societal
		Technological

All the articles share the dimensions of Government, Economy, Societal, and Technological as can be seen in table 4. Environmental factors were considered in two of the three with the remaining dimensions appearing only once. The report synthesizes these articles into the following five dimensions:

1. Governmental/Policy factors
2. Economic factors
3. Environmental factors
4. Societal factors
5. Technological factors

Each of these areas plays a key role in shaping how CE can be integrated into the construction industry. This chapter provides a comprehensive overview of each dimension, exploring how the current model of operation could be impacted with the adoption of CE frameworks to frame and coordinate its development. Such an overview is necessary to ensure that while developing baseline strategies, each dimension is considered separately and avoid or manage conflicting interventions (Wielopolski & Bulthuis, 2022).

Governmental factors play an important role in all construction activities. They provide rules and regulations that the construction companies need to comply with as well as incentives to nudge the industry in a desired direction. It is necessary for the government to keep up to date with the necessary innovations and have an overview of a bigger picture, acknowledging the global problems such as pollution and resource depletion (Zvirgzdins et al., 2019). By introducing policies that foster circular practices, governments can incentivize the construction sector to transition into new ways of operation (Alhawamdeh et al., 2024) (Gasparri et al., 2023) (Pomponi & Moncaster, 2017).

The economic dimension focusses on business models that ensure profitability for involved stakeholders. In the case of CE in the construction industry, the new practices present great long-term benefits in terms of general value of products and their operational costs, but this comes at the expense of high upfront costs. The current short-term cost structures based on quick Return on Investment (ROI) need to be re-evaluated in order to allow for operation under CE frameworks (Alhawamdeh et al., 2024) (Gasparri et al., 2023) (Pomponi & Moncaster, 2017). Utilizing economic dimension, it is possible to create effective strategies that can utilize opportunities for development.

The environmental dimension of CE focusses on reducing the negative impact on the environment by conserving resources, minimizing waste, and limiting pollution. In the light of construction sector, CE practices such as modular construction, loop thinking, and recycling contribute to reduced environmental pollution. A clear understanding of environmental dimension creates opportunities for justifying use of circular solutions as well as creating impactful policies (Pomponi & Moncaster, 2017) (Gasparri et al., 2023).

The societal dimension focusses on creating a society that is aware of principles of CE. More specifically, it involves educating people in ways to design and build in a circular manner, or how to maintain buildings to facilitate material reuse (Zvirgzdins et al., 2019). This dimension can impact the construction sector by sharing knowledge between practitioners about the available methods for operating in a circular manner and promoting circular ways of living with, for example, products such as service delivery models. This dimension provides an overview of the ways to enhance CE through engaging with stakeholders (Alhawamdeh et al., 2024) (Gasparri et al., 2023) (Pomponi & Moncaster, 2017).

The technological dimension of CE enables circular loops in construction by managing data and logistics necessary for circular processes and creating technologies that allow for mor circular practice. This dimension acts as a glue between others creating a synergy for value creation (Zvirgzdins et al., 2019). Understanding the technological dimension ensures that construction operations utilize the tools needed to implement CE effectively, bridging the gap between traditional practices and innovative solutions (Alhawamdeh et al., 2024) (Gasparri et al., 2023) (Pomponi & Moncaster, 2017).

3.6 Conclusion

This chapter presents the findings from the SLR to answer the following question SQ1: *"What does the Circular Economy entail in the context of the construction industry and how is the concept utilized in modern construction practice?".* This chapter has answered this question by 1. Providing the context and definition of the Circular Economy, 2. Giving information about the inherent characteristics of the construction industry that differentiates it from the other sectors, 3. Exploring the state of the art of CE application in construction, and 4. Synthesizing the findings to develop a construction industry specific definition of CE.

Looking into the topic of circular economy, the report first looked into its origins, exploring its development over the years into different frameworks for various sectors to use these precedents as a learning opportunity for the construction sector. The historical analysis showed that the concept has its roots in research from the early 1960s where the core principles focused on resource regeneration and loop thinking. Early strategies such as cradle to cradle or blue economy have mainly seen application in manufacturing and industrial sectors, focusing on the production of simple consumer goods. These industries were pioneers of CE, and their approaches can be used as a learning opportunity to achieve similar results in construction.

In a more modern setting, the definition of CE has evolved a bit further and has seen increased application in the world with the examples of worldwide documents such as 2015 EU circular economy strategy (Geissdoerfer et al., 2017). The report has uncovered some interesting trends in academic research where the research on the topic of CE has seen lots of similarities with the concept of sustainability with various articles going as far as using the two concepts interchangeably. The report has explored the similarities and differences between the two and has concluded that the focus of circularity lies mainly in economic and environmental factors while sustainability possesses a much more open-ended approach, and it advises against such diffusion of the topics as it introduces additional ambiguity and could become a barrier to the adoption of CE and thus should be avoided in the future. The research on the topic of CE was concluded by identifying the following definition of the concept: "An economy that preserves the value added to the products for as long as possible and virtually eliminates waste. The resources are retained within the economy when a product has reached the end of its life, so that they remain in productive use and create further value". Moreover, the analysis of the past applications of CE, looking into the previously successful industries and their ways of operation, has given the following two variables that have contributed to success of CE in the past: 1. CE thrives in industries with standardized processes and materials in controlled environments which allow for implementation of repetitive actions and monitoring, 2. CE greatly benefits from centralized mode of operation preferably with a centralized supply chain to simplify decision making and goal alignment. The inherent characteristics of the industries working on the consumer goods in the past aligned greatly with these requirements giving perfect environment for CE to thrive. These findings can be considered to be the enablers of CE, but it is necessary to look into whether or not they are applicable to the construction industry.

Following the research on the topic of CE, the chapter diverted its attention to contextualizing the construction industry as a whole with the aim of gaining a better understanding of the sector. First, the characteristics of the construction industry were analyzed and compared with the characteristics of the sectors historically successful in adopting circular practices that were found while exploring the topic of CE. This comparison showed that the construction industry possesses several inherent characteristics that differentiate it from other sectors.

First, the construction industry takes a project-based approach where each product is unique and operates under strict regulations which limit opportunities for CE implementation. Additionally, unlike consumer goods, the construction industry produces highly complex, large-scale projects that possess incredibly long lifecycles of up to tens of decades. The complexity of the projects makes it difficult to reproduce activities and standardize operations. Long lifespans further increase complexities, introducing additional uncertainties and opportunities for mistakes. According to the findings, the construction projects, in general, go through similar sequence of events in the following set of 5 phases:

- Design
- Manufacturing and supply
- Construction
- Operation
- End of Life (EOL)

Each of these phases is tied with a unique set of activities, challenges and opportunities for interventions for making the construction practice more circular. The chapter has given the general information about the tasks that are complete during each phase and the potential CE based strategies that can be applied at the time to accelerate the transition. Combining these findings with the information about stakeholders, barriers, and enablers of CE in the construction sector gives opportunities to identify unique relationships and create phase wise strategies for accelerating CE transition. Implementing the information about the phases of construction in the strategies makes it possible to create more detailed strategies that take into account the optimal timing for the interventions.

Additionally, the report has identified 5 key areas that influence the construction industry. Each of these areas have unique challenges and opportunities and can greatly influence the adoption of CE in the industry, thus they need to be considered while developing strategies to accelerate transition. These dimensions are as follows:

1. Governmental/Policy factors
2. Economic factors
3. Environmental factors
4. Societal factors
5. Technological factors

These areas can be used as a framework for organizing barriers and enablers as well as the stakeholders allowing for better tracing of important factors. For example, Economic barriers will likely be resolved with Economic enablers and the strategy for such an intervention will involve actors that possess economic power or interest. With this, report finalized contextualizing the construction industry in relation to CE. The paper shows the common characteristics of the sector, lifecycle of its projects, commonly used strategies and the areas of influence impacted by CE interventions.

The final step in answering SQ1 was exploring the current activities and strategies that can be seen in the construction industry that facilitate circular practices. These strategies were categorized in the following manner:

1. Design for Disassembly (DFD)
2. Building materiality
3. Construction processes
4. Building operation
5. Building optimization
6. End-of-life (EOL) strategies

The report has provided several strategies for each of the categories that can be seen in chapter 3.3.2. This segment is finalized by exploring the most utilized strategies to give an accurate overview of the state of the art. Findings suggest that, currently, strategies under DFD category, BIM, waste management and material selection are the most prevalent based on the SLR. It is important to state that this conclusion is based on only three separate articles and do not include information gathered from primary sources this it is recommended to further validate these findings.

To conclude the chapter, all the analyzed data was synthesized in the following construction industry specific definition of Circular Economy: “A construction designed, constructed, used, and reused with the entire lifecycle in mind. It is assembled with optimal materials that are produced in a closed loop system in a manner that allows for easy deconstruction. The construction is an economically responsible, efficient product with an optimal balance between the embodied energy and operational energy use while providing a comfortable environment for its users. It is powered by renewable energy sources and is maintained in an efficient manner to retain the value of the used materials allowing for future reuse of the building components and materials keeping resources in a closed loop.”

This definition requires the use of CE principles across all the phases of construction prioritizing optimization of resources but stressing the need for a balance between operational resource consumption and embodied energy alongside economic viability. For the remainder of the report, the paper will refer to circular construction in accordance with the given definition.

4. Stakeholders

Findings from chapter 3 indicate that adopting a lifecycle approach to construction management is a necessary step for enabling adoption of CE in the sector. This suggests the need for interventions during each phase of construction with contributions from the entire supply chain of the industry. Unfortunately, this complex multidisciplinary supply chain is seen as one of the largest barriers in the way of adoption of CE based on the findings of chapter 3.3.1 observable in Table 2, which stands in a way of following in the footsteps of industries such as industrial and manufacturing that can be seen as a benchmark for circular operations. According to Pomponi & Moncaster (2017) the construction industry is not a discrete discipline with its own isolated approaches, rather the sector deals with blurred theoretical boundaries that not only allows for multi or trans disciplinary methodology but requires them. Additionally, based on the findings of Brown et al. (2021) the majority of the actors in the construction supply chain lack experience and don't have the capabilities or the capacity to operate all the aspects that comprise circular propositions. This issue clearly shows the lack of information and knowledge accessible to the practitioners which can only be addressed by educating them through additional information exchange and communication with highly skilled and knowledgeable actors to strive for achieving circular practices in a collaborative manner (Eberhardt et al., 2020) (Brown et al., 2021). The engagement of the stakeholders determines the feasibility of CE initiatives and can act as both barriers and enablers for future steps.

Developing stakeholder engagement strategies is crucial for finding ways to bypass the barriers created by the complex supply chain of the industry as it allows for fostering collaboration through increased communication and coordination and enhancing trust among actors by aligning goals and working in a transparent manner. According to the findings of Baldew (2023) the first step towards developing engagement strategies is identifying all the relevant actors involved in the sector. This chapter aims to gain a better understanding of the complex supply chain with the intention of identifying relevant data that can help in clarifying potential conflicts, aligning interests, and identifying barriers and enablers that can influence CE practices as well as locating the actors that are necessary to be considered while developing circular solutions. The investigation is conducted with the aim of answering the SQ2: "*Who are the stakeholders involved in the construction industry and what power do they hold over adoption of CE?*". The chapter begins by providing a list of identified stakeholders from the academic articles during the SLR. Next, it analyzes the roles, responsibilities, and interests of the actors before exploring their power to influence the projects. Finally, the paper synthesizes the gathered data to map out the most crucial actors that need to be considered during the development of preliminary strategies.

4.1 Stakeholders of construction industry

This chapter synthesizes the findings from SLR to give a list of important actors found across the researched articles. It gives a complete overview of all the identified stakeholders to gather the most complete set of information before excluding specific actors based on their relevance in the consequent chapters. The findings show that construction stakeholders are involved during the entire lifecycle of the buildings starting from the design and manufacturing phase with actors like architects and engineers, construction phase with contractors and buildings, operational phase with the users of the buildings, and finally the EOL with demolishers and recyclers. Table 6 gives an overview of the identified actors after the analysis of the following articles (Eray et al., 2019) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022) (Gerding et al., 2021) and provides with a short description of perceived responsibilities and motivations for each stakeholder based on analyzed data. It is important to mention that all the reviewed articles contained information about the actors of the construction industry, but the chosen papers gave the most comprehensive overview of the stakeholders focusing on the full lifecycle. To give a general overview of the used articles, their research focusses on circularity and sustainability in construction with particular focus on the actors and their roles during the construction lifecycle. The articles utilized research methods such as case-studies, literature reviews, and interviews to gather their data with a balanced combination of information from academia and practice. Additionally, the information is gathered from the construction industries of the Netherlands, UAE, and Australia, giving a relatively wide overview of the actors. The given list of stakeholders in table 6 contains all actors related to the construction industry as a whole and doesn't make a distinction based on their relevance to the circular operations at this stage.

Table 6. The stakeholders of the construction industry.

Stakeholder	Description	Source
Project owner/developer/client	These actors are individuals or entities that initiate, finance and develop the projects. They are directly responsible for defining projects scope, budget and timeline for completion. Main interests include ensuring high quality, quick delivery, and adherence to the defined budget for the final projects.	(Gerding et al., 2021) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022) (Eray et al., 2019)
Investors	These actors oversee financing the projects in exchange for financial returns. The actors can range from private entities such as project owners to organizations such as banks. They are mostly interested in maximizing their return on investment (ROI) and minimizing risks of the project.	(Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Procurement experts	These are highly specialized actors working as consultants in charge of acquisition of resources such as services, materials, and work force. They are primarily concerned with procuring the right human	(Gerding et al., 2021) (Shooshtarian et al., 2022)

	and material resources for the project and provide their services for a monetary fee.	
Local and regional authorities	These actors oversee larger scale developments in the urban context. They enforce the building regulations and sometimes fund public projects. They are interested in achieving broad goals such as stimulating the economy and public safety. This is done through regulatory frameworks, strategic urban planning and funding.	(Gerding et al., 2021) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Policy makers	Policy makers are entities similar to governmental actors on varying scales. They create legal and regulatory frameworks to govern the construction industry. Policy makers are interested in ensuring social benefits through legal interventions as well as financial incentives and raised public awareness on relevant topics.	(Gerding et al., 2021) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Designers/architects	Designers and architects shape the construction projects with the focus on aesthetics, functionality, and compliance to the agreed upon requirements. They mainly provide services for a cost and can influence projects through creative designs.	(Gerding et al., 2021) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022) (Eray et al., 2019)
Urban planners	Urban planners oversee construction practices at an urban scale, ensuring that the projects comply with the broader urban development strategies. Their work is driven by the need to align urban fabric with the societal needs and provide necessary infrastructure to support communities. Their primary influence lies in developing plans that dictate where and how the construction projects can proceed.	(Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Project manager	The project managers are the actors that oversee the construction projects. Depending on the scale of the project these stakeholders can be either specially hired entities or just project owners. Their primary incentive is to deliver the project according to the required specifications, mainly looking at the quality, time of delivery, and costs. These actors are in touch with most of the construction supply chain and can	(Gerding et al., 2021) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)

	influence projects through facilitating better communication and collaboration.	
Contractor	Contractors are the entities overseeing the on-site activities during construction. They ensure onsite safety and efficiency. As hired stakeholders their primary interest is making profit. Contractors' primary influence lies in their ability to manage the process by adopting new technologies, hiring sub-contractors, and procuring specific human and material resources.	(Gerding et al., 2021) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Sub-contractors	Sub-contractors are specialized actors that provide services for monetary gain. They conduct important specialized and simple tasks during the construction process in accordance with the given specifications. Their expertise varies and can be used during the entire lifecycle of the construction projects including the maintenance and EOL tasks.	(Gerding et al., 2021) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Mechanical engineers (HVAC, Electric)	These are specialized actors that oversee production, installation, and maintenance of the buildings' mechanical systems such as elevators, HVAC. Etc. Mechanical engineers' primary objective is developing products according to client's specification for profit and they influence buildings through their delivered products, for example use of novel technologies and energy efficient systems.	(Eray et al., 2019)
Civil engineers (landscape, Structural)	Civil engineers are in charge of preparing building sites and developing complex structural systems that ensure the durability and safety of constructions. They are mainly concerned with the stability and durability of the end product and work for profit. Civil engineers can influence projects through their expertise on novel structural materials, ways of construction, and structural design options.	(Eray et al., 2019)
Material suppliers/distributors	These actors provide construction projects with the necessary building materials. They deliver their services for profit and are interested in a good image for further work. They influence the material choice of construction projects by supplying high quality materials that can come from secondary sources.	(Gerding et al., 2021) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Environmental consultants	Environmental consultants provide their expertise to the construction team on how to reduce the environmental impact of a project. These are niche	(Gerding et al., 2021) (Shooshtarian et al., 2022)

	actors that are becoming more relevant who aim to revolutionize construction practice. Their primary influence on the projects comes from their expertise about the environmentally conscious solutions, but they can only utilize this knowledge if they are invited to the construction team.	(Eray et al., 2019)
Sustainability advisors/experts	Circularity experts are actors with a great deal of knowledge about CE principles. They provide consultation services to the construction projects and provide with services that help optimizing the buildings lifecycle.	(Gerding et al., 2021) (Shooshtarian et al., 2022) (Eray et al., 2019)
Demolition operators	These are the actors that carry out deconstruction and demolition work at the EOL of the building. They work for profit and prioritize safe and efficient operation. Their influence lies in use of alternative procedures such as selective demolition to allow for easier reuse and recycling of the building components.	(Gerding et al., 2021) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Waste management/treatment experts	Waste management experts oversee recycling, reuse, and disposal of construction waste. They are mostly involved during construction and EOL phases and work for profit. Waste management experts can influence projects by providing advice for waste management strategies and operating in an environmentally conscious manner through reduction of landfilling and processing waste into secondary materials.	(Gerding et al., 2021) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Recyclers	Recyclers are EOL actors that process construction demolition waste (CDW) into secondary materials. Their interest lies in delivering alternative options that help in reduction of raw material consumption. Recyclers can influence the construction industry by making high quality secondary materials for use.	(Gerding et al., 2021) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Manufacturers	Manufacturers produce construction materials and components. They are for profit actors that deliver goods that match clients' specifications. They can influence projects by giving options to the construction team and operating in an environmentally conscious manner.	(Shooshtarian et al., 2022) (Eray et al., 2019)

Material scientists	These are specialized actors that develop new materials for the construction sector. They are disconnected from the general construction practices but can greatly influence sectors through the development of novel resources.	(Wielopolski & Bulthuis, 2022)
Transportation companies	Transportation companies are common actors present during all phases of construction. They are for profit stakeholders that are mainly interested in minimizing their own costs. They influence construction projects through use of optimized delivery routes and schedules with strategies such as just in time delivery.	(Shooshtarian et al., 2022)
Warehouse owners	Warehouses or storage facilities in general are an important part of the construction process. These facilities allow for storage of materials and equipment necessary for construction activities. These actors are profit driven and mainly care for maximizing efficiency and occupancy of their assets. They can greatly influence onsite logistics by optimizing transportation and delivery of necessary resources as well as contribute to the environmental impacts through offering storage and delivery of reclaimed materials.	(Shooshtarian et al., 2022)
Sub-contractors	Sub-contractors are, generally, specialized actors that carry out works on specific aspects of the project such as electrical works or plumbing. These stakeholders deliver their services for profit and are mainly concerned about efficient and safe delivery of their work.	(Gerding et al., 2021) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Construction workers	Construction workers are common actors that perform physical work on the construction site. They are mainly concerned about making a profit in a safe and fair working conditions.	(Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Users	These are the actors that occupy and utilize the finalized construction projects. They are mainly concerned with having access to durable, reasonably priced, high-quality spaces while retaining low operational costs. Users are the primary drivers of demand, thus their spending habits dictate the shape of the construction.	(Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Maintenance actors	These are the actors that extend the lifespan of the building through upkeep and repairs. Depending on the scale of the project, these stakeholders can be hired	(Wielopolski & Bulthuis, 2022)

	professionals or owners/users of the space. Their influence on the building lies in extending the effective life of the construction through maintenance activities.	(Shooshtarian et al., 2022)
Operation actors	Operation actors are the entities that manage day to day use and operation of the buildings ensuring functionality and comfort. These actors, depending on the scale of the project, can be private stakeholders working for profit, or owners of the space. Their influence on projects lies in data collection which gives necessary information for upkeep.	(Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Scrapyards/landfill owners	These actors oversee disposal and material recovery of CDW. They are for profit actors that operate under regulations for monetary reward.	(Shooshtarian et al., 2022)

The data analysis identified 28 stakeholders involved in the construction industry throughout the lifecycle of a building. Notably, this list of actors is partially summarized based on the personal interpretations during the research with exclusions for the stakeholders with similar titles or responsibilities. Additionally, the identified list is based purely on the dataset selected specifically for this research and a more extensive review is expected to identify a higher quantity of unique actors. In the subsequent paragraphs the paper synthesizes the findings by identifying and unifying the actors with overlapping roles or similar responsibilities. This is being done to develop a concise list of the most important actors grouped into specific categories, to simplify the findings and give key insights. The chapter follows this up by explaining the level of influence over projects from each actor and giving suggestions for how their actions could enable implementation of circular practices.

4.2 The key actors of the construction

This chapter synthesizes the findings from chapter 4.1 by systematically analyzing and combining the results to locate overarching categories and reducing complexity of the data while keeping the most relevant information. The list of 28 stakeholders is analyzed and grouped based on the roles and responsibilities to combine the actors with the complementary activities and functions together to make the list more concise and easier to interpret. Table 7 gives an overview of the combined list of 12 actors with a description for a reasoning for grouping. It should be noted that the given list of 12 stakeholders shows the important players of the general construction industry, and their selection is not based on their relevance to future circular operations. The report focusses on the generally relevant actors as it seeks to develop strategies for industry-wide transition for which it needs to consider the current state of the supply chain instead of designing the ideal future scenarios.

Table 7. The key actors of the construction industry

Grouped stakeholders	Grouped actors and reason for grouping
Project owner	This stakeholder was left unchanged due to the importance of the actor in decision making and the number of appearances during the SLR. Generally, this actor is the primary initiator of any project and cannot be grouped with anybody due to their decision-making power.
Financial actors	Financial actors are other stakeholders not grouped with anything. Generally, they provide the necessary capital for the construction projects and without their contributions it would be impossible to start the construction procedure. The financers could be entities such as: governments, banks, private equity firms, and individual stakeholders.
Governance actors	This category combines the following actors from the original list: Governmental organizations, Policy makers, and Urban planners. These actors share similarities in their methods for achieving goals, mainly they all develop rules and regulations that, in the case of construction industry, dictate land use, building codes, and sustainability requirements.
Project managements	This stakeholder is a grouping of original actors of: project manager and contractors. These actors oversee the planning, coordination, execution and monitoring of construction activities. Additionally, both actors primarily rely on communication to facilitate collaboration to deliver the projects under specified requirements.
Sub-contractors	Sub-contractors are an umbrella term for specialized actors that work on various parts of construction projects. This grouping includes: construction workers, and waste management/treatment experts, maintenance actors, and operation actors from the original list. While there is not a specific activity that unifies the grouped stakeholders, they are mainly hired by the general managers to deliver specialized tasks under given specifications. This category could include many more actors depending on the level of detail, for example cleaning, monitoring, logistics, etc.

Environmental experts	This category combines the environmental consultants and circularity experts from the original list. The actors under this category possess extensive understanding of environmentally conscious solutions and processes for the construction industry and work as consultants to provide advice during decision making.
Manufacturers	Manufacturers are the actors that provide the resources for the construction projects and are composed of the following actors from the original list: manufacturers, material scientists, mechanical engineers. All these stakeholders contribute to the innovation, development and application of goods for the construction industry. There is also an argument to consider these actors as sub-contractors, but this category works on broader solutions while sub-contractors execute onsite operations.
Design team	The design team includes the architects/designers and civil engineers from the original list. Both these actors are primarily involved during the design phase of the construction and are the primary stakeholders that create design solutions affecting functionality, aesthetics, and structural integrity.
Material suppliers	This is another category that has been left unchanged. Material suppliers provide the construction team with the essential resources for the buildings. These actors dictate the availability of primary and secondary resources, costs, logistics, and greatly impact environmental impact of building projects.
EOL actors	This category combines demolition experts and recyclers from the original list. Generally, these are the EOL actors that complement each other's work. The collaboration between these actors ensures the retention of value of secondary materials and allows for efficient reuse.
Users	This is the final unchanged category. These actors are involved in any construction project during the operation phase, and they dictate the trends of the construction market.
Resource storage and logistics	The final category combines the warehouse owners, transportation companies and scrapyard/landfill owners from the original list. This grouping was created based on each actor's involvement in the logistics of moving, storing and disposing of construction materials.

As a final step of this chapter, the paper aims to evaluate the importance of the stakeholders based on their level of influence over the project. Unfortunately, it was difficult to evaluate the actors according to these categories while being clearly supported from the given literature as most of the articles recognize the importance of the stakeholder identification and involvement as is the case from Baldew (2023) and Wielopolski & Bulthuis (2022), but do not dive into the specific actors that need to be involved. Moreover, articles repeatedly recognized the importance of time of involvement of actors within depth knowledge of circularity, particularly in the case of using the expertise of EOL stakeholders during the design stages to maximize circular practices in the project (Gerding et al., 2021).

The main findings with regards to the decision-making power of stakeholders from the projects are drawn from the case studies of Gerding et al. (2021), who analyzed three circular construction projects. Case studies suggest that in all three cases, apart from the client, the actors with the highest decision-making power were the traditional stakeholders involved in the project team such as contractors and the designers. The actors that were recognized to have the least amount of decision-making power are as follows:

- Circularity experts
- Dismantlers
- Specialists
- Suppliers
- Sub-contractors
- Reclamation experts.

This paper has also concluded that irrespective of whether the client takes the initiative in terms of promoting circularity, other actors, such as the contractor and project manager who possess high decision-making power in a project team, can still act on and steer towards adaptation and implementation of circular practices (Gerding et al., 2021).

Synthesizing the findings from Gerding et al. (2021), the report draws the following three conclusions. 1. The actors that are in communication with many other stakeholders generally have high decision-making power, 2. The initiators of the project, such as project owner, have the most important vote during decision making, and 3. Expert actors that are hired to execute specific work, for example sub-contractors, generally aren't involved in decision-making processes. Applying these assumptions to table 7, it is possible to estimate the general decision-making power of each actor which are presented in table 8.

Table 8. Decision making power of stakeholders (highest to lowest)

Stakeholders	Explanation
Project owner	The project owners are the primary initiators of the project that set the goals and the budget and based on assumption 2 above they make the final decisions on the major aspects.
Governance actors	While not directly involved in a project, governance actors create the rules and regulations that the construction industry must comply with. They influence decisions by providing incentives or regulatory limitations.
Financial actors	Financial actors provide the funds for the project with the expectations for ROI. These financial commitments influence the project's budget and either create or take away opportunities for specific construction practices.
Project managements	Project management actors are central stakeholders directly involved in collaboration with most of the supply chain of the construction practice. Based on assumption 1, these actors have high decision-making power due to their central position in a project team and possession of large quantity of project specific information.

Design team	The design team possesses relatively high decision-making power in the early phases of construction due to the extensive communication and collaboration with other actors.
Users	While users needs directly dictate what is being built, they rarely have direct decision making power without the ownership of a project. Despite this, in countries like the Netherlands, they can legally oppose certain practices thus retaining some power.
Manufacturers	These actors do not comply with any of the 3 made assumptions. While not being directly involved in the decision making, they dictate the market conditions with the manufactured goods.
Material suppliers	Similar to manufacturers, these actors dictate the market conditions by making specific materials available in different quantities and costs. Material suppliers and manufacturers possess similar amount of power.
Environmental experts	These actors generally take an advisory role so they aren't directly involved in the decision making, but they can increase their power by becoming part of a design team in the early stages of construction.
Sub-contractors	Sub-contractors are hired to perform specialized tasks, and their decision-making power doesn't go beyond the services they provide.
Demolition operators	These actors influence projects mainly during the EOL phase and currently lack extensive communication with other actors. Literature generally suggests that these actors can be very influential to adoption of CE if involved in the design phase of construction.
Resource storage and logistics	These actors possess limited communication with any other stakeholders, and they simply support operational activities but do not influence projects directly.

Due to the high costs associated with the construction related activities stakeholders such as project owners and investors have the highest influence over the project as they are directly responsible for financing activities and set goals and requirements. Unfortunately, generalizing the findings from Gerding et al. (2021), their expertise in CE is lacking and their motivation traditionally lies towards the financial aspects of the project. While these actors are a big driving force behind the decisions, studies show that irrespective of whether the client takes the initiative in terms of promoting circularity, other actors, such as the contractor and project manager, can still act on and steer towards adaptation and implementation of certain CE (Gerding et al., 2021).

Stakeholders such as governmental organizations and policy makers hold significant regulatory power. While they might not be involved in each project in detail, they create overarching laws, policies, and incentives that need to be followed by all other stakeholders which gives them significant influence over any construction project (Owojori & Okoro, 2022). Unfortunately, while these actors hold significant power, their knowledge of CE may vary significantly, often appearing underwhelming which can be seen in all three cases presented by Gerding et al. (2021).

The remaining highly influential stakeholders are the traditional construction actors such as project managers, contractors, and other members of the design team (Gerding et al., 2021). These actors are engaged in intense collaboration with lots of communication and typically are connected to other more specific actors with less power. They control the project planning design and execution putting them in an influential position. While their specific knowledge about CE may vary, their experience and involvement in the sector allows them to be the driving force behind CE implementation. Lee et al. (2023) and Wielopolski & Bulthuis (2022) have found unique correlation between the involved stakeholder's capital and size. Particularly, smaller organizations have higher incentives to adopt CE strategies in their practice and tend to be more innovative, which could allow them to create better business models allowing them to serve as an example and become drivers for CE transition.

It is important to note that the actors with the highest degree of expertise over CE such as, consultants and EOL stakeholders, seem to have the least amount of power in the traditional construction practice (Gerding et al., 2021) (Owojori & Okoro, 2022). Ideally, these actors should be given opportunities to enter the project team to more effectively influence the construction projects, utilizing their expertise (Gerding et al., 2021). Moreover, they should be brought into a project team as early as the start of the design phase to increase their contribution to a project creating more opportunities for implementation of CE principles.

4.3 Conclusion

This chapter has conducted extensive analysis of the supply chain of the construction industry to answer SQ2: *"Who are the stakeholders involved in the construction industry and what power do they hold over adoption of CE?".* The preliminary analysis has identified a list of 28 stakeholders presented in table 6. After grouping the various stakeholders based on similarities of conducted actions and approach to simplify this list, the paper identified 12 key actors of the construction supply chain. These actors are as follows:

- Project owners
- Governance actors
- Financial actors
- Project management actors
- The design team
- Users
- Manufacturers
- Material suppliers
- Environmental experts
- Sub-contractors
- Demolition operators
- Resource storage and logistics actors

Moreover, the paper gave general information about the interests of these stakeholders alongside the simple strategies they could utilize to facilitate CE in construction.

In order to answer the second part of SQ2, the report conducted analysis to evaluate the decision-making power of each actor, but the selected literature contained limited information to sufficiently answer this. The report used the analyzed data to make following 3 assumptions: 1. The actors that are in communication with many other stakeholders generally have high decision-making power, 2. The initiators of a project such as project owners have the most important vote during the decision making, and 3. Expert actors that are hired to execute specific work, for example sub-contractors, generally aren't involved in decision making processes. These assumptions were later applied to the refined list of stakeholders to evaluate their decision-making power. The findings suggest that the following actors possess the highest decision-making power over the project.

- project owners
- governments
- financial actors

On the other hand, specialized actors such as sub-contractors and resource storage and logistics actors possessed the least amount of power. These findings are based on assumptions on limited amount of data and thus might need further validation in the future.

The given information is sufficient to provide an answer to SQ2. The findings up until now provide a foundation for the report contextualizing both the construction industry and CE. The following chapters focus on the problems and solutions by analyzing the barriers and enablers seen in academia and comparing it to the already identified list of barriers and enablers.

5. Barriers

The primary objective of this paper is the development of strategies that can accelerate the transition of the construction industry into a circular way of operation. The previous chapters have used the findings from the SLR to provide contextual information about Circular Economy, the construction industry, and the current state of CE in the explored sector. Based on the previous research, the paper found that 1. The primary objective of CE is optimization of systems to reduce/eliminate waste by keeping the materials in a closed loop, 2. The concept has been applied successfully in the past in industries such as manufacturing, making it possible to learn from the past, 3. There are various fundamental differences between construction industry and the traditional sectors that successfully utilize CE, making the current frameworks insufficient, 4. Construction industry does utilize several CE strategies but in isolated cases without any large scale application. Moreover, the report provided a concise definition of CE applicable to the construction industry, gave a full lifecycle overview of the construction projects, and identified the key areas of the sector that would be influenced by the adoption of CE. Finally, the paper explored the complex supply chain of the sector to identify the key actors. All these findings are key variables that need to be considered while developing solutions.

In this chapter the report shifts its focus to the problems in the way of adoption of CE in the construction industry. A clear understanding of a problem is necessary to ensure that the developed strategies are effective and do not overlook key hurdles in the way of CE adoption. This is particularly relevant for this research as many of the issues such as regulatory constraints and project-based approaches are unique to the construction industry and differ significantly from the other sectors that utilize CE principles (Minino et al., 2018), (Lee et al., 2023), (Eberhardt et al., 2020), (Pomponi & Moncaster, 2017) thus the existing data doesn't give an accurate overview the challenges the industry might face. The paper addresses the issue of barriers by resolving SQ3 *"What are the most important barriers that limit the widespread adoption of CE practices in the construction sector that halt the industry wide transition?".* This question is tackled in the following manner: First, the report summarizes the already available information about the barriers that can be gathered from the previous chapters. Following this, the paper presents the findings of the SLR to give an exhaustive overview of the barriers identified in academic literature. Finally, the chapter evaluates the barriers to identify the most critical hurdles and arranges them in a descending manner from the most relevant to the least relevant to uncover the most critical obstacles in the way of CE implementation. This approach is taken with the aim of adhering to the principles of pragmatism showing the most relevant barriers, Pluralism giving the overview of all of the identified hurdles in a transparent manner, and contestation by presenting the findings that don't directly align with one another.

5.1 Summary of the available information about the barriers

Before diving into the literature review, it is useful to provide a summary of the already available information to explore what is already known about the barriers of CE. The previous chapters aimed to give an overview of the CE as a tool and the characteristics of the construction industry as well as the actors of the sector. While not directly touching on the subject of the barriers, the findings can be synthesized to give a general overview of the identified problems.

The report has come across various issues that could be categorized as a barrier to the adoption of CE in the construction industry. Generally, these issues can be attributed to the ambiguity surrounding the definition of the concept of CE, the limited implementation of the concept or the inherent characteristics of the industry.

First, as mentioned in the beginning of the report, there is a lack of universally accepted definition for Circular Economy within the construction industry which has led to the confusion around the topic and its development in various different directions without a unified goal (Mhatre et al., 2021) (Banihashemi et al., 2024) (Adams et al., 2017). This was clearly seen in the diffusion of the topic with the concept of sustainability, where, despite the differences, several authors were seen using the two concepts interchangeably. Such ambiguity is a clear barrier that can hinder the adoption of CE by creating inconsistencies in the understanding and application of its principles. This further leads to fragmentation of efforts for the development and use of the subject, limiting options for collaboration and large-scale implementation. Finally, the lack of a clear definition makes the tool seem less attractive for the investors due to the perceived uncertainties, weakening the business case for CE.

Additionally, it was clear that, despite the opportunities that the concept of CE provides to the construction industry, the tool sees very limited implementation in real-life applications. Several reasons can be attributed to this problem: 1. The industry operates under strict safety regulations that require it to use high quality materials and limits options for the use of secondary resources due to the technological limitations related to the material recovery (Lee et al., 2023), 2. There are little to no market incentives thus the companies operating in circular manner gain little competitive advantage (Pomponi & Moncaster, 2017).

Moreover, the inherent characteristics of the construction industry seem to create many challenges for CE implementation. First, the industry is very traditional and risk averse (Eberhardt et al., 2020) which creates hesitancy in committing to the transition to circular operation. Next, the industry produces highly complex, large scale, expensive projects that possess significantly longer lifespans compared to the products of the industries historically successful in CE based operations (Pomponi & Moncaster, 2017) (Eberhardt et al., 2020). Such characteristics bring in large amounts of uncertainty, weakening the business case for the investment into such practice. Moreover, each project is unique, limiting the option for use of standardized materials and operations. Each of the given characteristics can be viewed as a barrier that complicates the transition to a CE based construction industry.

Finally, the fragmented supply chain of the construction sector (Lafhaj et al., 2024) makes it difficult to implement overarching strategies as each actor is self-interested and, according to the findings of chapter 4, it is difficult to guarantee equal distribution of benefits after the systematic transition, thus it is expected to see many actors opposing to change.

Besides the described general issues, the synthesis has revealed a total of twenty-five barriers. The full list of the identified hurdles can be viewed in Appendix B. It is interesting to compare these findings to the barriers identified during the SLR to validate the previous findings and look for differences to give the most complete overview of the problems that stand in the way of systematic transition of the construction industry.

5.2 Systematic Literature Review of the Barriers

While the previous chapter has given a general overview of the barriers that can be seen in the construction industry with regards to the CE, now the report explores the academic perception of this issue by conducting a systematic literature review.

Before presenting the findings from the literature, it is useful to give some background information about the analyzed articles to ensure transparency and avoid misrepresenting the data. The analysis mainly utilized information from 12 academic articles. These papers were conducted with the primary focus on the construction and adjacent sectors, with slight exclusions in the works of Eberhardt et al. (2020) who addresses the origins of CE frameworks in the manufacturing sectors and Minunno et al. (2018) who also includes manufacturing sectors with the focus on prefabrication. A large portion of the included articles gathered data with the SLR approach and validated the findings with the mix of case studies, surveys, and expert interviews. Finally, the report ensures that the information used in the chapter is up to date by selecting the dataset with the earliest used publications from 2017 in case of Adams (2017) and Pomponi & Moncaster (2017).

The analysis identified a total of 121 barriers, which were reduced to 35 after removing duplicates and combining similar barriers. The full list of 35 barriers can be seen in appendix B, while table 9 provides a shortened list of 10 most commonly recurring ones. Table 9 gives a small description of each identified barrier and provides a reference to each article used to acquire the given data.

Comparing the findings to the previously identified barriers, it is possible to see some overlap. Table 9 can be linked to the 7 barriers identified in the previous chapter while there is an overlap of 15 barriers when comparing the full lists presented in Appendix B. Besides the similarities, a key difference can be seen in the case of the "Unclear definition of CE" where it is seen as a major barrier according to the synthesis of the previous findings, but this is not reflected in the findings of the new SLR. This is speculated to be due to the researched articles being based on the inputs from the industry practitioners who, according to the previous research, have limited knowledge and understanding of the topic of CE. This speculation creates a scenario where it is impossible to determine if the participants had the same definition of CE leading the researchers to overlook the lack of definition as a barrier.

Table 9. The key barriers in the way of adoption of CE in the construction industry

Barriers	Description	Source
High upfront adoption costs	The shift to circular mode of operation requires a significant commitment from the industry requiring large upfront investments for developing new technologies, infrastructure, and training. Such financial burden can make companies and investors hesitant to invest into circular practice without clear financial benefits.	(Lee et al., 2023) (AlJaber et al., 2023) (Kanters, 2020) (Pomponi & Moncaster, 2017) (Zvirgzdins et al., 2019) (Ding et al., 2023) (Minunno et al., 2018) (Owojori & Okoro, 2022) (Shooshtarian et al., 2022)

Unclear financial case	Due to the novelty of CE in this construction industry and its focus on long-term benefits, its benefits are highly uncertain and unpredictable. Moreover, it is difficult to quantify the gains from circular mode of operation, further increasing the perceived uncertainty and discouraging investors that primarily focus on economic gains.	(Adams et al., 2017) (Lee et al., 2023) (AlJaber et al., 2023) (Kanters, 2020) (Pomponi & Moncaster, 2017) (Zvirgzdins et al., 2019) (Ding et al., 2023) (Minunno et al., 2018)
Lack of knowledge/expertise about CE	The stakeholders of the construction industry possess only limited understanding of the CE, its benefits, and way of operation. Such limited knowledge leads to overlooking potential environmental/economic gains and creates hesitancy to invest in circular mode of operation. Additionally, limited experience and training, for example in fields such as circular deconstruction, limits the potential for use of circular principles.	(Adams et al., 2017) (Lee et al., 2023) (AlJaber et al., 2023) (Kanters, 2020) (Zvirgzdins et al., 2019) (Minunno et al., 2018) (Owojori & Okoro, 2022) (Eray et al., 2019)
Lack of mechanisms for material recovery	Currently the construction industry lacks options and systems for material recovery and reuse of secondary materials. This creates fluctuations in the price of reclaimed materials making the uncertain and less favorable than the virgin counterparts. The lack of systems for material recovery also makes it difficult to distribute, store, and sell the high-quality secondary materials, disincentivizing industry from reuse and pushing it further towards using finite resources.	(Adams et al., 2017) (AlJaber et al., 2023) (Kanters, 2020) (Ding et al., 2023) (Owojori & Okoro, 2022) (Shooshtarian et al., 2022) (Eray et al., 2019)
Lack of interest	The current profit driven construction industry lacks awareness of the benefits of CE and doesn't see the benefit in altering their traditional approaches. Without a clear incentive to shift into circular mode of operation the stakeholders have no reason to move away from the established practices discouraging innovation and investment into CE.	(Adams et al., 2017) (Lee et al., 2023) (AlJaber et al., 2023) (Kanters, 2020) (Minunno et al., 2018) (Owojori & Okoro, 2022) (Shooshtarian et al., 2022)
Limited demand for circular products	Without the demand for circular construction there is no incentive for the industry to operate In this manner, which results in the limited demand for circular products. In turn, this creates a mismatch between the supply and demand, disincentivizing businesses from investing in circular practices and materials. Without the market support for circular products the industry will proceed to operate	(Lee et al., 2023) (AlJaber et al., 2023) (Kanters, 2020) (Ding et al., 2023) (Owojori & Okoro, 2022) (Shooshtarian et al., 2022) (Eray et al., 2019)

	with conventional methods, slowing the transition.	
Fragmented supply chain	The complex, fragmented supply chain of the construction industry makes coordination and communication between the stakeholders difficult, limiting the information exchange and slowing goal alignment. Such fragmentation gets in the way of developing comprehensive solutions necessary for a successful transition into a circular mode of operation leading to surface level solutions and window-dressing without any actual progress towards circular construction practice. Without a clear united front, the sector risks overlooking opportunities and implementing necessary solutions effectively.	(Adams et al., 2017) (AlJaber et al., 2023) (Eberhardt et al., 2020) (Zvirgzdins et al., 2019) (Ding et al., 2023) (Minunno et al., 2018)
Unclear policy support	The absence of clear, consistent regulations incentivizing operation withing CE principles creates uncertainties that discourages investment into CE initiatives. Currently, the industry and its stakeholders don't face regulatory pressures that urge them to transition into circular practice delaying the transition. The ambiguity and inconsistencies in the regulations only increase uncertainties related to the topic of CE and creates lack of perceived urgency.	(Lee et al., 2023) (AlJaber et al., 2023) (Kanters, 2020) (Minunno et al., 2018) (Owojori & Okoro, 2022) (Shooshtarian et al., 2022)
Lack of information/scaled up case studies	The lack of industry specific information and absence of real-world, scaled-up solutions makes it difficult to perceive the feasibility and benefits of circular operation. Without sufficient information and clear evidence of successful implementation of the concept, the industry will continue operating in the traditional manner as it lacks the ability to make informed decisions about the validity of CE as a new way of operation.	(AlJaber et al., 2023) (Zvirgzdins et al., 2019) (Ding et al., 2023) (Minunno et al., 2018) (Shooshtarian et al., 2022) (Eray et al., 2019)
Complexity of buildings	The construction industry produces multi-layered, composite structures that are designed to stay operational for decades, using a high-quality materials. It uses highly complex connections and technologies to ensure safety and durability of the products making dismantling and material recovery difficult. The current buildings limit the options for closing the loops for the construction materials and	(Adams et al., 2017) (AlJaber et al., 2023) (Ding et al., 2023) (Shooshtarian et al., 2022) (Eray et al., 2019)

	require novice solutions to adapt to circularity requirements.	

These are the 10 most commonly occurring barriers found during the systematic literature review. Table 9 arranges the barriers in a descending order in accordance with the literature citation analysis, where "High upfront costs" stands at the top with it being mentioned in nine articles while "Complexity of buildings" being last with only five appearances in the research.

The general trend can be seen where the most frequently mentioned barriers revolve around the economic viability of CE as well as the available knowledge on the subject. The identified barriers are not lone standing, on the contrary they are systemic by nature as can be seen in the example of "Unclear policy support" or "Fragmented supply chain" where these issues are deeply intrenched within the industry, which speaks on the complexity of these challenges and highlights the need for deeper solutions that can address the root causes of the barriers. Moreover, additional complexity of these barriers lies in their interconnectedness where many of the barriers such as "Unclear policy support" exacerbate the hurdles such as "Lack of interest" showing the need to treat them as "wicked problems". These complexities suggest that the identified barriers cannot be treated as individual problems and they require, as suggested by Wielopolski & Bulthuis (2022), strongly interdisciplinary design processes that integrate a broad variety of disciplines from the entire supply chain to create multi-faceted solutions through coordinated efforts. To allow for making the most informed decisions with regards to resolving the hurdles, the report aims to further analyze the barriers to evaluate their relevance. This is done to explore the relationships between the barriers and gather information that could be relevant for forecasting the effects of the interventions, for example how will implementing circular policies impact the "Lack of interest" or the "Unclear financial case". Such forecasting can allow for developing strategies for addressing the root causes of the barriers for most optimal results.

5.3 Evaluation of the barriers

This chapter aims to further analyze the previously identified barriers in an attempt to clarify what hurdles have the greatest impact on the adoption of CE in the construction industry. Due to the inherent subjectivity of the evaluation process it is difficult to identify a singular sequence of importance. The research attempt to learn from the gathered academic literature looking into their evaluation of the barriers as well as the used methodology to develop its own strategy for assessment.

The reviewed articles have used multiple approaches to quantify the relevance of CE barriers but despite the large quantity of available methods used during the research, there was no clear consensus about the sequence of relevance. Generally, the papers recognize the complexity of the task of evaluation, and they all give different perspectives highlighting the aspects that contribute to the complexity of the task, but none of them provide a concrete list of importance.

A common step among the papers includes categorizing the barriers into smaller subgroups. This step is most evident in the research of AlJaber et al. (2023) and Adams et al., (2017) where the barriers are grouped in the following 7 categories:

- Technical
- Regulatory
- Economic/Market
- Social
- Implementation
- Support/Promotion

This method of categorization is used for combining similar variables to simplify their evaluation and make it easier to compare large quantities of variables in a structured manner increasing the clarity of the research. Coincidentally, the given categories closely resemble the dimensions of CE presented in table 5 of chapter 3.5. This method can be potentially beneficial for in the next part of the report for simplifying the process of matching barriers and enablers.

Besides categorization, the articles generally undergo some form of frequency analysis where they aim to quantify how often the identified barriers appear in academic literature. This step is conducted under the assumption that the most often mentioned barriers are more likely to be more relevant and complex to overcome. The clearest use of this method can be seen in the research of AlJaber et al. (2023), where after categorizing the barriers in the previously given groups the authors conducted an analysis exploring the number of appearances of each category of barriers to quantify their relevance. Their findings suggest that Technical, Economic, and Awareness-related issues possess the highest relevance, which matches the results of the analysis given in the previous chapter. The report utilizes the given method as a first step for evaluating barriers as the Literature Citation Analysis performed in chapter 5.2 is a form of a frequency analysis and was used to identify 10 of the most reoccurring barriers from the original set of 35.

The last explored method of evaluation was found in the works of Lee et al. (2023) in the form of a 4-quadrant model analysis. This model identifies the most critical variables by evaluating them on two key criteria. In the case of Lee et al. (2023) the paper compared the CE strategies used in the Taiwanese construction industry based on their importance and adoption, putting them on a grid with the respective 2 axis and splitting the diagram into 4 quadrants. While this method can be viewed as subjective and doesn't directly show the clear sequence of importance, depending on the selected criteria of evaluation, it gives a clear overview of the variables with suggested areas of focus.

The paper will utilize the 4-quadrant model to evaluate the identified barriers. The chosen 2 key criteria for comparison are as follows:

- Literature Citation Analysis: This criterion evaluates the barriers based on their frequency of appearance in scientific literature. Large number of appearances suggest the recognition of the obstacle by many researchers as a major problem. This criterion ensures that the results of the analysis align with the existing body of knowledge. Additionally, this method allows for easily quantifiable evaluation, reducing the subjectivity in the process.
- Interdependence analysis: This criterion judges the barriers based on the degree to which it is linked with the other problems taking into account the quantity of the connections as well as the causality. This criterion is selected due to the fact that certain issues act as the root causes that exacerbate other challenges and resolution of the said barriers can potentially lead to solutions to multiple related hinderances.

Table 9 already contains sufficient information for evaluating barriers based on the first criterion. The second criterion requires the paper to explore the relationships between the barriers and thus will contain a certain degree of subjectivity. Table 10 depicts the identified connections between the barriers. The numbers in the top row coincide with the numbers of each of the barriers presented in the left column while the last column presents the number of identified connections between the barriers. This is a subjective evaluation based on the available information found during the literature review. The full overview of the reasoning behind the connections can be viewed in Appendix C.

Table 10. Interdependence analysis

	1	2	3	4	5	6	7	8	9	10	N
1. High upfront adoption costs	X	X	X	X	X		X	X		X	8
2. Unclear financial case	X	X	X	X	X	X	X	X	X	X	10
3. Lack of knowledge/expertise about CE	X		X	X	X	X		X	X	X	8
4. Lack of mechanisms for material recovery	X	X	X	X	X	X		X			7
5. Lack of interest	X	X	X	X	X	X		X			7
6. Limited demand for circular products		X	X	X	X	X		X			6
7. Fragmented supply chain	X	X	X	X		X	X	X		X	8
8. Unclear policy support	X	X	X	X	X	X	X	X	X	X	10
9. Lack of information/scaled up case studies	X	X	X					X	X		5
10. Complexity of buildings	X	X	X	X			X	X		X	7

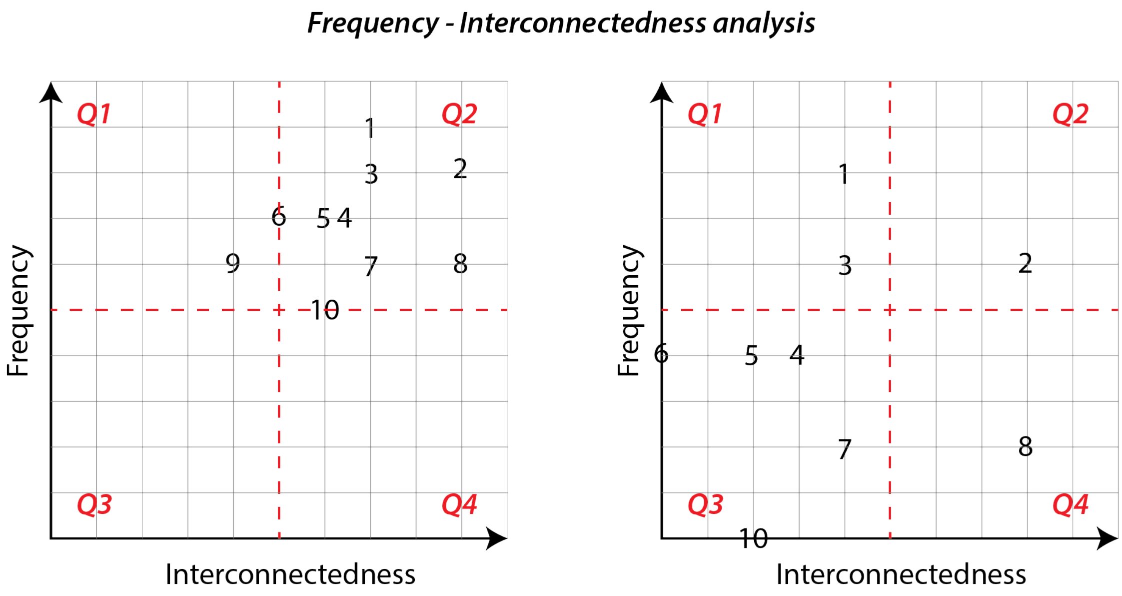
Combining the results for the Literature Citation Analysis and the Interdependence Analysis in the 4-quadrant model, it is possible to proceed with the evaluation of the barriers.

The high number of appearances in the literature indicates the recognition of the barrier from the academic community suggesting the high perceived importance and real-world impact of the issue. Conversely, a low number of appearances may speak about the lack of recognition of the issue due to the nuanced nature of the hurdle or the lack of available information about the topic. In the case of the latter this could be due to a research gap and indicates the necessity of additional research as such problems could be viewed as unknows unknowns and in if such barriers are strongly related to other issues, they could pose a significant threat.

High number of interconnections with other barriers indicate the need for prioritization for addressing the issue as they impact the implementation of CE from various directions and require systemic solutions. Thes hurdles are likely deeply rooted in the industry's structure, practice, and the supply chain and have a cascading effect on other problems.

Low interconnectedness between the barriers can be seen in the case of isolated issues that have a more limited influence and impact on the entire construction industry. These challenges can be viewed as the symptoms of the bigger underlying issues and are most effectively dealt with by prioritizing the root cause.

Figure 8 contains the Frequency-Interconnectedness diagram where each barrier is placed in accordance with the previously conducted analysis seen in table 9 and table 10. This evaluation is based purely on the selected literature in case of frequency analysis and personal evaluation in case of interconnectedness. The barriers evaluated in this analysis have already gone through previous screening with the intention of minimizing their number. This is evident in the perceived high importance of all of the analyzed issues as all of them are placed in Q1 or Q2 (see figure 8 left side). In an attempt to make a more detailed comparison, the report zooms into the second quadrant and repeats the evaluation process as shown on the right side of figure 8. It is important to note that the research recognizes the high relevance of all the gathered barriers and only seeks to make comparisons between them to identify the highest priority issues compared to others.



1. High upfront adoption costs
2. Unclear financial case
3. Lack of knowledge/expertise about CE
4. Lack of mechanisms for material recovery
5. Lack of interest
6. Limited demand for circular products
7. Fragmented supply chain
8. Unclear policy support
9. Lack of information/scaled up case studies
10. Complexity of buildings

Figure 8. Frequency-Interconnectedness analysis/ 4-Quadrant model

Q1 – the barriers located in the first quadrant are the commonly recurring hurdles that have an isolated effect on the construction industry. These problems are likely caused by larger underlying issues and can be effectively dealt with by eliminating the root cause instead of treating the symptoms.

Q2 – These barriers are well recognized hurdles that are “wicked” by nature. These problems have a significant effect on the entire industry as each issue is connected with others and threatens to have a cascading effect on the entire supply chain if not properly dealt with. Barriers under this category require multifaceted strategies focused on long-term solutions.

Q3 – these are the isolated issues that possess limited relevance and can be addressed through one-off solutions that doesn’t require strong focus.

Q4 – These are the less recognized issues that are intertwined with many other challenges and have the potential to significantly hinder opportunities for CE adoption. These problems require a better understanding and strong prioritization as they can be viewed as unknown unknowns or the significant problems that the industry is not fully aware of.

The sequence of importance of the barriers in accordance with the frequency-interconnectedness analysis is as follows.

High priority barriers consist of economic, policy and knowledge related issues that directly align with the general consensus of academia. These issues should be the primary focus when developing solutions and require an in-depth approach through collaborative efforts of the entire supply chain.

- Unclear financial case
- Unclear policy support
- High upfront adoption costs
- Lack of knowledge/expertise about CE

Medium-High priority barriers include market-related challenges and logistical issues. While scoring below the above depicted hurdles, these issues still possess significant relevance and heavily influence the adoption of CE. The barriers related to this relevance level are as follows:

- Fragmented supply chain
- Lack of mechanisms for material recovery
- Lack of interest

Lastly, Medium-Low priority barriers, while by no means lacking relevance, score comparatively low for both frequency of appearances in the literature and interconnections with other barriers. The barrier of complexity of buildings is particularly difficult to judge as this is an inherent characteristic of the industry and its relevance can be put higher due to its connections with other factors, but the limited appearances in the academia places it in this category.

- Complexity of buildings
- Limited demand for circular products
- Lack of information/scaled up case studies

5.4 Conclusion

The list of the barriers shown above concludes the research of this chapter and allows to give an answer to the SQ3 *"What are the most important barriers that limit the widespread adoption of CE practices in the construction sector that halt the industry wide transition?"* giving not only the overview of the most important barriers but also providing a sequence of importance. With this, report has sufficient information about the problems that need to be resolved by the final deliverable, and it can move onto exploring the final unexplored variable for the solutions in the form of enablers to get a full understanding of the problem, the context of the industry and the available tools that can be used to achieve the end goal.

6. Enablers

The report has given a full context of the construction industry and the circular economy and its historic application. It has identified the relevant actors of the sector and developed tools to better understand and address the problems surrounding CE in the shape of dimensions of construction and the phasing of the projects. The previous chapter addressed the primary problem of the report by exploring the barriers that get in the way of adopting CE in the industry. This research has led to the identification of the 10 most crucial hurdles, their sequence of relevance, and the rationale behind their severity alongside the suggested approaches that need to be taken when dealing with them.

The last missing variable necessary for addressing the main RQ is the knowledge about the enablers in the shape of available opportunities and strengths of the sector. A good understanding of the enablers provides the most complete overview of the industry and allows it to face its challenges without overlooking potential solutions. This chapter aims to gain a full understanding of this topic by answering SQ4: *"What are the enablers that can enhance the widespread adoption of CE in the construction industry?".* The report mimics the methodology of the previous chapter by first synthesizing the already available information to identify the potential enablers to the adoption of CE in the construction industry. This is followed up by the SLR that gives an exhaustive list of enablers mentioned in the academic literature. Contrary to the previous chapter, the report doesn't seek to evaluate the enablers as this is perceived to be pointless as enablers are tools that are meant to resolve a particular task, and their relevance is dependent on the problems that need to be resolved. This sequence of steps allows the paper to validate the previous findings and gives the most complete information adhering to the principles of pragmatism, pluralism, and contestation.

6.1 Summary of the available information about the enablers

The conducted research up until this point has touched upon various strategies that are already in use or possess a great potential to aid the implementation of circular operations in the construction industry. These topics can mainly be seen discussed in chapters 3.2 and 3.3 and include a clear definition of CE, various new ways of operations, and the success factors that greatly contributed to the implementation of CE in the past in other sectors such as centralized supply-chains or highly monitored and controllable environments for manufacturing. In total, the synthesis has identified 35 enablers touching upon all phases of construction across various dimensions of CE with varying levels of detail. These enablers are seen to possess a great deal of potential for influencing the construction industry in accordance with the synthesis and they can be seen presented in appendix D. The following enablers had the highest level of perceived relevance due to the previously identified problems and their backing from the academic articles.

First, while looking into the general context of the CE, its origins, and its previous applications, aiming to gain a better understanding of the topic, the paper identified various problems with its true definition. It was made clear that the topic of CE has been diffused with the concept of sustainability over the years, and it lacks a clear unified definition particularly in the case of the construction industry where all the research surrounding the topic has been conducted in isolation lacking a unified direction. To combat this, the paper has given the following construction industry specific definition of CE: "A construction designed, constructed, used, and reused with the entire lifecycle in mind. It is assembled with optimal materials that are produced in a closed loop system in a manner that allows for easy deconstruction. The construction is an economically responsible, efficient product with an optimal balance between the embodied energy and operational energy use while providing a comfortable environment for its users. It is powered by renewable energy sources and is maintained in an efficient manner to retain the value of the used materials allowing for future reuse of the building components and materials keeping resources in a closed loop.". The given definition was designed based on the synthesis of the research about the topic of CE and the contextual information of the construction industry, and it aims to give the industry a unified direction to direct its efforts to with the aim of achieving transition into circular mode of operation.

Additionally, while exploring the origins of circular economy, the research has identified the previously successful sectors that have managed to implement CE principles in their operations which were mostly tied to the production of consumer goods. Upon further investigation the paper has linked the successful application of the concept in these industries to the following variables:

The explored industries possessed centralized supply chains and decision-making models. These characteristics had made an impact on the efficiency of information flows, communication, collaboration, and goal alignment creating the ideal environment to optimize the systems, promoting accountability, and making commitments all of which are necessary factors for adoption of CE principles.

Additionally, these industries often focused on the production of consumer goods in the highly controlled, standardized environments that utilized simple materials and conducted easily repeatable tasks. These environments allowed for easy adjustments to the operations with the aim of optimizing the production practice which, in turn, helped in designing out waste and maximizing the value of the materials.

These enablers were seen to be the most promising based on the synthesis, but as mentioned before, the relevance of an enabler is highly dependent on the problems that need to be resolved. In the case of the identified highest impact barriers, only the enabler of centralized supply chain and decision making is directly applicable, but this doesn't mean that it's not possible to learn from other factors. Particularly in the case of the definition, while this was not seen as a relevant enough barrier that needed to be addressed based on chapter 5, a clear definition of the goal greatly aids any process. The report aims to show all the identified opportunities to adhere to the principle of pluralism and build a most complete base of knowledge for the future researchers to build up from.

6.2 Systematic Literature Review of the enablers

This chapter presents the findings of the systematic literature review to give an overview of the academic perception of CE enablers in the construction industry. The review has selected 17 articles from the original dataset to derive the conclusions based on the relevance of the given information. The selected research papers were primarily focused on the application of CE principles within the construction demolition waste (CDW) management, the built environment, manufacturing and the real estate sector focusing on the strategies, barriers, and enablers for the implementation of the concept. Similar to the dataset used in exploring the barriers, the most commonly used data gathering method in the selected papers was Literature review or the SLR while case studies, surveys, and interviews were utilized for validating the findings. Finally, efforts were taken to ensure the used information was up to date as the oldest articles in the dataset were published no more than 10 years ago in the case of Adams (2017), Pomponi & Moncaster (2017), and Minunno et al. (2018).

In total the chapter has gathered 174 enablers which was limited to the total number of 48 after removing the duplicates and merging differently worded enablers that addressed the topic. Table 11 contains the results of the SLR with all the identified enablers, their short description, and the source of where the information was gathered from.

Table 11. Enablers of CE in the construction industry

Enabler	Description	Source
Design tools and guidance	A structured framework for stakeholders of the industry that informs them about the ways in which the concepts of CE can be applied to in real life.	(Adams et al., 2017) (AlJaber et al., 2023) (Shooshtarian et al., 2022)
Measurement tools	Practical tools that can be used to quantify the benefits of CE such as Life Cycle Assessment (LCA) or BIM.	(Adams et al., 2017) (Zhang et al., 2022) (Banihashemi et al., 2024) (Barbhuiya & Das, 2023)
Incentive schemes	Schemes aimed at making CE principles more attractive through financial and non-financial benefits.	(Adams et al., 2017) (Lee et al., 2023) (Zhang et al., 2022) (AlJaber et al., 2023) (Ghufran et al., 2022) (Barbhuiya & Das, 2023) (Shooshtarian et al., 2022)
Incentives to use secondary materials	Financial and non-financial benefits aimed at encouraging the use of secondary resources.	(Adams et al., 2017) (Zhang et al., 2022) (AlJaber et al., 2023) (Eberhardt et al., 2020) (Banihashemi et al., 2024) (Barbhuiya & Das, 2023) (Shooshtarian et al., 2022)
Best practice case studies	Increased quantity of high quality research on real-world projects showing the feasibility and benefits of CE strategies.	(Adams et al., 2017) (Lee et al., 2023) (AlJaber et al., 2023) (Wielopolski & Bulthuis, 2022)
Awareness raising campaigns	Organized efforts for educating actors of the construction industry principles, benefits, and practice of CE.	(Adams et al., 2017) (Lee et al., 2023) (Zhang et al., 2022) (AlJaber et al., 2023) (Ghufran et al., 2022) (Shooshtarian et al., 2022)
Technology for material recovery	Advanced tools and systems that facilitate efficient material recovery at EOL such as BIM or RFID.	(Adams et al., 2017) (Zhang et al., 2022) (AlJaber et al., 2023) (Eberhardt et al., 2020) (Zvirgzdins et al., 2019) (Banihashemi et al., 2024) (Ghufran et al., 2022) (Minunno et al., 2018) (Shooshtarian et al., 2022)

High value secondary materials	Increased availability for secondary materials through developments of markets for recovery and promotion.	(Adams et al., 2017) (Zvirgzdins et al., 2019) (Shooshtarian et al., 2022)
Take back schemes	Systems for increasing manufacturer responsibility at the end of products useful life allowing for retaining the value of products.	(Adams et al., 2017)
Clear business case	A clear economic rationale demonstrating the economic viability and benefits of adopting CE practice.	(Adams et al., 2017) (Lee et al., 2023) (AlJaber et al., 2023)
Collaboration	Cooperative approach between the actors of the construction industry with active participations and information exchange aimed at achieving CE goals.	(Adams et al., 2017) (AlJaber et al., 2023) (Eberhardt et al., 2020) (Kanters, 2020) (Pomponi & Moncaster, 2017) (Barbhuiya & Das, 2023) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Systems thinking	Holistic approach to decision making taking into account the interdependencies between variables to optimize systems.	(Adams et al., 2017)
BIM	The use of building information modeling for optimizing workflow through enabling better design, planning and management of constructions.	(Adams et al., 2017) (AlJaber et al., 2023) (Banihashemi et al., 2024) (Minunno et al., 2018)
Policy support and regulations	Frameworks that incentivize and promote circular practices through regulations, standardization, incentive schemes and planning.	(Lee et al., 2023) (AlJaber et al., 2023) (Kanters, 2020) (Banihashemi et al., 2024) (Ghufran et al., 2022) (Barbhuiya & Das, 2023)
Education and research	Driving innovation by making the available information more accessible while extending the knowledge base through research to find new ways of overcoming existing challenges.	(Lee et al., 2023) (AlJaber et al., 2023) (Zvirgzdins et al., 2019) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Material passports/Material databases	Facilitating recycling, reuse, and better management of building materials through material tracing and informed decision making.	(Lee et al., 2023) (Zhang et al., 2022) (AlJaber et al., 2023) (Banihashemi et al., 2024) (Barbhuiya & Das, 2023) (Shooshtarian et al., 2022)
Long lasting building design	Extending the effective lifecycle of constructions and components through innovative practices and material use.	(Zhang et al., 2022) (Eberhardt et al., 2020) (Zvirgzdins et al., 2019) (Ghufran et al., 2022) (Shooshtarian et al., 2022)
Early consideration of EOL activities	Emphasizing the need of planning deconstruction, material recovery, and reuse at the design stage of the construction projects.	(Zhang et al., 2022) (Eberhardt et al., 2020) (Zvirgzdins et al., 2019) (Banihashemi et al., 2024) (Ding et al., 2023) (Minunno et al., 2018) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Selective demolition	Controlled process of deconstruction that allows the retention of highest value for materials and reduces waste.	(Zhang et al., 2022)

Standardization	Creating a set of uniform practices, reproducible practices that facilitate the reuse, recovery, and recycling of materials and components while simplifying the construction process.	(Zhang et al., 2022) (AlJaber et al., 2023) (Eberhardt et al., 2020) (Banihashemi et al., 2024) (Barbhuiya & Das, 2023) (Minunno et al., 2018) (Shooshtarian et al., 2022)
Setting goals	Creating a clear set of goals and measurable targets for the stakeholders giving a unified direction to strive for.	(Zhang et al., 2022)
Restrictions on landfilling	Policy approach discouraging disposal of CDW and encouraging more circular methods such as material recovery and recycling.	(Zhang et al., 2022)
Sufficient infrastructure	Developing sufficient facilities, systems, and networks that simplify the use of circular practices.	(AlJaber et al., 2023) (Eberhardt et al., 2020) (Minunno et al., 2018)
Material selection/Substitution	The use of appropriate materials for each project with the aim of optimizing material flows and reducing unnecessary emissions.	(Eberhardt et al., 2020) (Zvirgzdins et al., 2019) (Shooshtarian et al., 2022)
Adaptable / Flexible building design	Creating constructions and building components that can be modified, reused, or repurposed over time, reducing waste and extending the effective lifecycle of resources.	(Eberhardt et al., 2020)
Lifecycle approach to scoping	Increased consideration of the full lifecycle of constructions to ensure the decisions made at each stage don't have trickledown effects on other stages.	(Eberhardt et al., 2020) (Zvirgzdins et al., 2019) (Wielopolski & Bulthuis, 2022)
Sufficient building team selection	Choosing the right actors for the projects that have sufficient skills, knowledge, and commitments to operating in circular manner to facilitate collaboration and drive innovation.	(Eberhardt et al., 2020)
Modular design	Unique construction practice that increases the options for adaptable design, efficient disassembly, and use of resources.	(Eberhardt et al., 2020) (Banihashemi et al., 2024) (Minunno et al., 2018)
Offsite construction / Prefabrication	An alternative method for manufacturing that Is conducted in controlled environments allowing for more effective use of resources, waste reduction, and options at EOL.	(Eberhardt et al., 2020) (Minunno et al., 2018) (Shooshtarian et al., 2022)
Component reuse	Extending the effective lifecycle of the building components by keeping it in a closed loop and reusing it in alternative construction projects.	(Eberhardt et al., 2020) (Zvirgzdins et al., 2019)

Optimized shapes and dimensions	Technical enabler focusing on standardizing geometry of construction components to simplify projects and increase options for EOL activities.	(Eberhardt et al., 2020)
Layer independence in buildings	A new way of visualizing constructions by separating materials based on their effective lifespans in layers., allowing for easier maintenance, material recovery, and adaptability.	(Eberhardt et al., 2020)
Sharing schemes	Collaborative use of resources, materials, and equipment among multiple users, aiming to optimize their use and reduce waste.	(Eberhardt et al., 2020) (Zvirgzdins et al., 2019)
Communication	A basic strategy that is key for effective collaboration, information exchange, and stakeholder engagement.	(Kanters, 2020) (Pomponi & Moncaster, 2017) (Barbhuiya & Das, 2023) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Ownership models	Rethinking the traditional ownership structures and adoption systems such as Product As a Service which shifts the focus from selling to providing a service to encourage manufacture for more durable and easier serviceable products.	(Pomponi & Moncaster, 2017) (Ding et al., 2023)
Procurement strategies / Tendering agreements	Inclusion of CE principles during the tendering phase allow development and selection of the most appropriate construction teams and designs.	(Pomponi & Moncaster, 2017) (Shooshtarian et al., 2022)
Transparency	Open access and sharing of relevant information with regards to construction practice and materials to foster trust, allow for informed decision making, and promote accountability among stakeholders.	(Pomponi & Moncaster, 2017)
Specialized maintenance activities	Proactive strategies for care of construction projects aimed at optimizing performance, extending life, and facilitating reuse or recycling of high value components and materials at EOL.	(Zvirgzdins et al., 2019)
Sustainable energy sources	The use of alternative sources of energy that are less reliant on fossil fuels.	(Zvirgzdins et al., 2019)
Digitalization	Use of modern tools to digitize the existing and the future building stock to provide a clear overview of the existing world and allow for informed decision making with regards to building processes and waste reduction.	(Banihashemi et al., 2024)

Material tracking	Use of technological systems such as RFID chips to monitor, record, and track the status of construction materials and components throughout their lifecycle allowing for easier maintenance and resource management.	(Banihashemi et al., 2024) (Elghaish et al., 2023) (Minunno et al., 2018) (Shooshtarian et al., 2022)
Block chain technology	A powerful tool that provides a secure, transparent platform for managing relevant information that can be used optimize logistics activities, improve trust, and facilitate collaboration.	(Elghaish et al., 2023)
Optimized logistics	Efficient management of material flows covering both forward and backward logistics to improve material tracking and utilizing available tools and technologies to close loops.	(Elghaish et al., 2023) (Ding et al., 2023) (Shooshtarian et al., 2022)
Creating environment for innovation	Establishing collaborative relationships between multidisciplinary actors aimed at fostering development and creating of novice solutions. The better building initiative can be seen as an example framework for this.	(Wielopolski & Bulthuis, 2022)
Waste management strategies	Practices aimed at minimizing waste generation, optimizing the use of resources, and ensuring proper handling of byproducts of construction.	(Shooshtarian et al., 2022)
Extended manufacturer responsibility	Shifting the task of waste management from society to the manufacturers with the aim for incentivizing development of more durable, reusable, recyclable, and less harmful products that retain high value of materials and stay withing the circular systems longer.	(Shooshtarian et al., 2022)
Markets for secondary materials	Creating platforms and mechanisms for recovering, storing, trading, and reusing materials that have already been used in construction projects. These systems are aimed at reducing the reliance on virgin materials and reducing waste by providing attractive alternative options to the industry.	(Shooshtarian et al., 2022)

Analyzing the findings, it is possible to make the comparisons to the results of chapter 6.1. In total, 23 out of 35 previously defined enablers can be tied to the ones presented in table 11 hinting on the validity of the previous research. The identified similarities can be seen in Appendix D. Unlike the similarities between barriers, it was not possible to find clear patterns between similar enablers. In the case of differences, two primary enablers stand out. First, the clear definition of the CE as a concept was suspected to be highly relevant based on previous research, primarily due to the lack of definition being seen as a major barrier but this enabler wasn't identified in the literature research. The mismatch could be explained similarly to the case of the barriers where if the industry doesn't recognize the problem behind the fragmented development of the concept it will not seek a solution. Additionally, the previous synthesis has found a unique enabler in the case of allowing smaller companies to be the market drivers for the circular practice. This enabler was based on the assumption that the smaller companies that often concentrate on more niche markets could see circular operations as a way to build a unique brand and increase visibility on the market (Lee et al., 2023). Additionally, they are viewed to be less resistant to change due to the less established processes which allows them to experiment and seek for more cost-effective strategies (Lee et al., 2023). Moreover, they tend to have more direct customer relationships which could help them to implement the CE business model that focuses on longer benefits such as take-back models (Kanters, J. 2020). These factors create unique environments where these companies could become the industry leaders in CE further developing their business case and promoting the viability of this model. This is a very specific solution that has yet to gain traction in academic research, but it seems to be very promising due to its practical implications.

6.3 conclusion

In conclusion, this chapter has given an overview of the barriers identified by both personal evaluation and academic research. It has given an answer to SQ4: *"What are the enablers that can enhance the widespread adoption of CE in the construction industry?"* by giving an exhaustive list of 48 opportunities that can be utilized to battle the barriers of CE. With this, the paper has given information about all the necessary variables that go into developing strategic interventions for adopting CE in the construction industry. Now it diverts its attention to synthesizing these findings to identify the relationships between enablers and barriers to explore the unique patterns that can be utilized to address SQ5 *"What is the relationship between the barriers, enablers, and the actors of the construction industry and how can these connections be utilized to accelerate the industry wide transition?"* and the primary RQ *"How can the construction industry accelerate the sector wide transition into a more circular way of operation using the principles of Circular Economy".*

7. Strategy development

With the conclusion of the previous chapter, the report has presented all the results of the research establishing a construction industry specific definition of CE, exploring the characteristics of the construction sector, identifying the most crucial barriers in the way of adoption of CE, and giving an overview of the enablers that can be utilized to achieve the systematic transition to the circular mode of operations. With all the necessary variables in place, the paper diverts its efforts to combining and synthesizing the findings to utilize the given information to answer SQ5: *"What is the relationship between the barriers, enablers, and the actors of the construction industry and how can these connections be utilized to accelerate the industry wide transition? " .* The given SQ5 is dealt with by identifying the relationships between barriers, enablers, and stakeholders and using the given connections to identify the pathways towards adopting CE in the construction industry.

The large quantity of the available information for the synthesis makes analyzing the data more complex and tedious. To bypass this issue, the chapter aims to utilize the previously identified method of categorization seen in the works of AlJaber et al. (2023) and Adams et al., (2017), which allows the research to group the variables into small, more manageable clusters and identify overarching themes for comparison and interconnections. In the case of the report, enablers, barriers, and stakeholders can be grouped based on the following two categories: 1. How do the given variables impact the construction industry looking at the "Dimensions of CE" framework given in chapter 3.5. This looks at the primary impacts of the barriers and enablers as well as the motivations and influence of the actors. 2. During what stage of the construction projects' lifecycle do the given variables appear and have influence based on the framework of "Phasing of construction projects" given in chapter 3.4. This category explores the effectiveness of enablers during particular stage of construction, the impact of barriers based on time, and the influence of the actors during different time periods giving the information relevant for understanding the effective timing of strategic implementations.

The chapter takes a sequential approach, where it first categorizes all the relevant variables starting from barriers, then enablers, and finally stakeholders. Next, the paper develops the general approach for addressing each of the issues taking into account the available information. Finally, the chapter applies the developed methodology to create 10 strategic intervention plans for each of the barriers taking into account the available strengths and giving general approaches for stakeholder engagement.

7.1 Categorization of Barriers

This chapter attempts to synthesize the findings with regards to the barriers of the CE in the construction industry to categorize the hurdles into specific dimensions of CE as well as group them based on their relevance in a particular stage of construction practice. The paper goes over barriers one by one giving each a specific category based on "Dimensions of CE" and "Phases of construction" while also providing a short rationale about the reasoning behind it. All of the identified connections are made based on personal bias and understanding of the topic in accordance with the reviewed articles.

Unclear financial case – This barrier stresses the importance of the ways to quantify the economic benefits of CE to make the practice more attractive for businesses to adopt. This is a clearly "*Economic"* barrier, prioritizing the financial performance of the construction projects. Moreover, it appears to have implications across the entire lifecycle of the construction projects, but due to the importance of perception of financial viability to the stakeholders, the early stages such as "*Design stage*" could be considered to be the most relevant, as this is when the actors make commitments about the scope of the project.

Unclear policy support – This barrier is assigned to the "*Governmental/Policy"* category as it directly touches upon the problems stemming from the absence of clear regulations, incentive schemes, and legal frameworks that encourage use of CE principles, but it has the potential to affect all dimensions of CE. Looking into the temporal considerations, the lack of supportive policies impacts the entire lifecycle of the construction practice as policies incentivize the actors to make alterations to the regular operations. The early stages of construction could be considered to be the most relevant as if the actors commit to the CE approach early on this can have effects down the line, but, in general, the barrier of unclear policy support is apparent during the entire lifecycle.

High upfront adoption costs – This is a clearly "*Economic"* barrier that discusses the issues stemming from the necessity of significant initial investments for the development of new equipment, processes, and skills necessary for operating in a circular manner. Generally, this barrier influences the entire lifecycle of the project, but it could be argued that due to the "*Construction"* phase being the most work, time, and cost intensive involving a large quantity of actors such as skilled workers, construction managers, supervisors, etc., this stage of construction could be most impacted by the problem.

Lack of knowledge/expertise about CE – This barrier describes the problems stemming from the limited knowledge of the construction industry practitioners about the topics of CE and their inability to operate circular practices due to their lack of expertise on the subject. This hurdle can be assigned to the following two categories: 1. "*Societal*" this category of barriers summarizes the hurdles stemming from the limited understanding and awareness of the CE topic which can be directly applied to this barrier, 2. "*Technological"* This category combines the issues stemming from the lack of available knowledge. While the limited understanding of the topic is a clearly "*Societal"* issue, without the availability of sufficient information it is impossible to educate the practitioners which also connects it to the "*Technological"* category. Additionally, looking at the timeframe of the construction projects, it can be said that the barrier of limited knowledge and the lack of expertise is impactful across the entire lifecycle of the project. If necessary, the relevance of this issue could be tied to be the highest at the design stage as decisions during this time give more options for CE practice at later stages, but its wrong to assume that this is the only time this problem should be considered.

Fragmented supply chain – This is an inherent characteristic of the construction industry observable through lack of collaboration and coordination between the stakeholders of the sector, this issue also includes the problems of limited information transfer, lack of communication, and lack of trust. This is a primarily a "*Societal"* problem, where the self-interested industry practitioners operate in isolation limiting knowledge exchange and reducing awareness surrounding the topic of CE. Additionally, the primary motivation for the actors is tied to monetary gains connecting them to "*Economic"* dimension. The problem of the fragmentation of the construction industry's supply chain could be argued to become worse when the quantity of actors in the project increases as this causes more confusion and complicates the processes further. Based on this assumption, "*Construction"* and "*Manufacturing and supply"* phases could be considered to be most relevant for this barrier, but with each construction project being different and involving different stakeholders, it is difficult to justify limiting this issue to only these phases.

Lack of mechanisms for material recovery – This is a complex problem that includes the limited availability of the necessary infrastructure, regulations, or systems for the utilization of secondary materials of the construction industry. This is a multifaceted barrier that could be connected to "*Governmental/Policy"* category as the absence of sufficient environments for operation are often tied to the lack of sufficient policies. It can be also related to the "*Technological"* category as it can be argued that the current system does not yet have the tools necessary for utilizing secondary materials. Similarly, the lack of available infrastructure and systems make the secondary materials less financially viable giving it small connections to the "*Economic*" category as well. Looking into the time considerations, the barrier has impact on various phases. Mainly, without available systems aiding the use of secondary materials, the actors during the "*Design stage"* might be hesitant to commit using recycled materials. Moreover, without sufficient systems in place, it is difficult to recover materials from the buildings at the "*EOL stage*" and bring it to the facilities that "*Manufacture and supply*" the new circular products. In general, due to the complexities stemming from the barrier during many phases it would not be advised to limit it to a singular stage of construction.

Lack of interest – This is a "*Societal"* barrier that involves the general lack of motivation and interest of the stakeholders to adopt CE principles which could be due to their limited understanding and awareness around the topic of circular operations or "*Economic"* factors such as the preference of conventional methods due to the associated costs. The lack of interest can be present during any stage of construction from any of the stakeholders limiting the opportunities for categorization into phases of construction but, due to the higher perceived relevance of the early phases, *"Design phase"* can be considered most influential.

Complexity of buildings – This is a "*Technological"* barrier stemming from the inherently large scale, long lifespans, and the use of composite materials in construction projects. These issues get further in the way of use of secondary materials as they complicate recovery and recycling necessitating innovative solutions. Looking into the phases when this barrier is the most relevant, it is difficult to give a direct answer as the inherent complexity of construction projects impacts its entire lifecycle. If looking at the problem from the standpoint of solutions, it could be argued that the "*Design phase*" is the most important because, as stated by Banihashemi et al. (2024), the decisions made at this stage have long-term consequences and can affect factors such as construction, operation, maintenance, and EOL.

Limited demand for circular products – This is a simple issue stemming from the lack of interest in the use of circular practices and materials, which can in turn create supply issues due to the limited "*Economic"* viability of producing products that are not demanded on the market also tying the barrier to the temporal category of "*Manufacturing and supply"*.

Lack of information/scales up case studies – this is a "*Technological"* barrier that touches upon the issues of lack of data from the real-world examples of CE application to demonstrate the feasibility of the concept. Looking at the timeline of the projects, the lack of available information is definitely most impactful at the earlier stages of construction as without sufficient knowledge it is easy to make decisions that overlooks opportunities and makes commitments that have implications for the entire lifecycle of the project. Due to these reasons, the barrier could be assigned to the "*Design stage*" category, but the lack of sufficient information has an impact on the entire lifecycle.

Summarizing the findings, all of the 10 most important barriers have been categorized based on two different variables. Table 12 contains the overview of the categorization based on "Dimensions of CE".

Table 12. Categorization of barriers based on 5 Dimensions of CE

Barrier	Governmental/Policy	Economic	Societal	Technological	Environmental
Unclear financial case					
Unclear policy support					
High upfront adoption costs					
Fragmented supply chain					
Lack of knowledge/expertise about CE					
Lack of mechanisms for material recovery					
Lack of interest					
Complexity of construciton					
Limited demand for circular products					
Lack of information/scaled up case studies					

A large portion of the barriers can be seen assigned to the Economic dimension as it seems to be the most relevant factor in the way of CE adoption. Surprisingly, none of the barriers were assigned to the Environmental dimension which suggests that majority of the decisions are made based on pragmatism looking into the availability of tools to alter operation processes and the potential financial benefits of the transition without showing any considerations for the environmental benefits. These categories of barriers will be used to simplify comparisons with the large quantity of enablers looking for opportunities that address similar topics and thus have the potential for combating specific barriers.

Looking into the phases of construction, it could be implied that this category was not directly applicable to the complex barriers as majority of the issues could not be tied down to particular set of construction phases and their impact could be observed across the entire lifecycle of the construction projects. The primary finding from this process is that the "*Design*" stage of the construction projects seems to possess higher level of relevance for most of the barriers as the early interventions have implications for the entire lifecycle of the construction and thus strategies influencing this phase of construction should be prioritized.

7.2 Categorization of Enablers

Following the categorization of the barriers, the report diverts its attention to grouping enablers based on their relation to the dimensions of CE and effectiveness of their application during a particular phase of construction. In total, the chapter aims to categorize 48 variables into subgroups of 5 Dimensions of CE and 5 phases of construction to simplify the process of relating them to the barriers in the final part of this chapter. All of the identified connections are made based on personal bias and understanding of the topic in accordance with the reviewed articles.

Due to the large quantity of the available enablers, the report has opted out from reviewing each of them one by one in a written manner similar to the way it was done in the case of barriers instead, the findings are presented in the form of table 13 where each enabler is related to a specific Dimension of CE and a Phase of construction in a concise manner. In the case of Dimensions of CE, the following was the rationale behind each group:

- Governmental/Policy category consists of the enablers related to the role of the governments and policies for creating supportive tools and frameworks for CE. They include incentive schemes, policy support, and regulations that drive CE adoption. Generally, enablers under this category relate to more than one dimension as the policies can be directed to various areas such as finances, environmental issues, or organizational problems.
- Economic enablers focus on the financial aspects of CE aiming to create viable business models, incentivize CE practice, and prove the economic competitiveness of the solutions. It looks at both the strategies that guarantee profits as well as the tools that assist in the process of quantifying the benefits.
- Societal enablers are tied to the human aspect of the Circular Economy. These factors encourage change through collaboration, increased awareness, education, and general human interactions and processes. The enablers in this category look into alternative modes of operation that are less apparent in the current industry.
- Technological enablers are directly concerned with the available tools for the CE transition ranging from the availability of sufficient information to the advanced technologies for material tracking.
- Environmental enablers focus on reducing the environmental impact of the construction projects through resource efficiency and all the strategies aimed at lessening the overall ecological footprint of the constructions. This dimension is relatively broad and some of its aspects can be seen in the majority of the explored enablers.

The information presented above was used as a rationale for categorization which was done based on personal perceptions about the topic and their relation to one of the described subgroups. The categories depicted in **bold** letters in table 13 present the most relevant subgroups for the enablers showing ties to multiple categories at the same time.

The rationale for the categorization of enablers into the phases of construction was based on the perceived opportunities of implementing solutions during a specific time and their potential impact from this implementation. The variables in each subgroup can be implemented during the assigned time and possess a high perceived chance for success. It is important to note that various enablers, similar to the barriers, can be assigned to more than one phase of construction, as can be seen in the case of enablers such as incentive schemes. Such enablers provide various opportunities to accelerate the adoption of CE across the entire lifecycle of the projects but, in an attempt to specify their relation to the particular phase of construction, table 13 depicts the most influential phases in **bold** letters.

Table 13. Categorization of enablers based on Dimensions of CE and their effectiveness during phases of construction

Enabler	Dimensions of CE	Phase of construction
Design tools and guidance	**Technological**	Design phase
Measurement tools	**Technological,** Economic	Design phase
Incentive schemes	**Governance/Policy,** Economic	All phases
Incentives to use secondary materials	**Governance/Policy,** Economic	**Design phase,** All phases
Best practice case studies	**Technological,** Societal, Economic	**Design phase,** all phases
Awareness raising campaigns	Societal	**Design phase,** all phases
Technology for material recovery	Technological	**End of Life phase**
High value secondary materials	**Technological**, Economic, Environmental	Design phase, **Manufacturing and supply phase,** End of life phase
Take back schemes	**Governmental/Policy,** Economic	Construction phase, **End of Life phase**
Clear business case	Economic	**Design phase**, all phases
Collaboration	Societal	**Construction phase,** all phases
Systems thinking	**Societal**, Environmental	Design phase
BIM	**Technological,** Societal	**Design phase**, all phases
Policy support and regulations	**Governmental/Policy,** Economic, Societal, Environmental	All phases
Education and research	**Societal**, Technological	All phases, **Design phase**
Material passports/Material databases	Technological	**Design phase**, All phases
Long lasting building design	**Technological,** Environmental	Design phase

Early consideration of EOL activities	**Societal,** Technological	Design phase
Selective demolition	**Technological,** Environment	End of Life phase
Standardization	Governmental/Policy, **Technological,** Economic	Design phase, **Manufacturing and supply phase**, Construction phase
Setting goals	Societal	Design phase
Restrictions on landfilling	**Governmental/Policy,** Environmental	End of Life phase
Sufficient infrastructure	**Governmental/Policy,** Technological	**Design phase,** all phases
Material selection/Substitution	Environmental	Design phase
Adaptable / Flexible building design	Environmental, **Technological**	Design phase
Lifecycle approach to scoping	Environmental, **Societal,** Economic	Design phase
Sufficient building team selection	Societal	Design phase
Modular design	**Technological,** Environment, Economic	Design phase
Offsite construction / Prefabrication	**Technological,** Environment	Manufacturing and supply phase
Component reuse	Environmental, **Technological**	Construction phase, **End of life phase**
Optimized shapes and dimensions	Technological	Manufacturing and supply phase
Layer independence in buildings	**Technological**, Environmental	Design phase
Sharing schemes	Societal	Construction phase, **Operational phase**
Communication	Societal	**Construction phase**, All phases
Ownership models	**Societal,** Economic	Operation phase
Procurement strategies / Tendering agreements	Governmental/Policy, **Economic**	**Design phase**, Manufacturing and supply phase
Transparency	Societal	All phases
Specialized maintenance activities	**Technological**, Environmental	Operational phase
Sustainable energy sources	Environmental	Construction phase, **Operational phase**
Digitalization	**Technological,** Societal	**Construction phase,** All phases
Material tracking	Technological	**Manufacturing and supply phase,** Construction phase, End of life phase
Block chain technology	**Technological,** Societal	**Construction phase,** All phases
Optimized logistics	Technological, **Societal**, Environmental	**Construction phase,** all phases

Creating environment for innovation	**Societal,** Technological	**Design phase,** All phases
Waste management strategies	Environmental	Construction phase
Extended manufacturer responsibility	**Governmental/Policy**, Societal, Economic	End of life phase
Markets for secondary materials	**Economic,** Technological	End of life phase

Some general remarks can be made about the patterns observed during the categorization of the barriers. Many of the variables can be seen to be related to more than one dimension of CE or Phase of construction showing the multifaceted nature of the suggested solutions. Additionally, the variables related to policies, economic viability, and awareness seem to have larger quantity of relations with many categories. This observation can be explained with the nature of the given enablers with: 1. Policies giving opportunities for interventions at any time for any of factor of construction practice when worded correctly, 2. Economic factors determining the viability of any intervention, for example denying certain solutions because the project simply cannot afford it, 3. Lack of awareness making actors blind to the available options, where if the stakeholders are not aware of the specific solutions they will simply be ignore them. Moreover, looking at the categories of phases of construction, the "*Design phase*" clearly shows the largest relevance with it having relations to the largest number of enablers. This observation further proves the previously identified notion that the interventions during the design stage have implications for the later stages of construction. Finally, a large portion of the enablers can be tied to the environmental category showing the direct link between CE and environmental benefits.

While the report has made an effort to show the most important categories for each of the enablers, it is important to note that will utilize all the available information while corelating them to the barriers.

7.3 Categorization of Stakeholders

Finally, the research categorizes the important stakeholders of the construction industry based on their relation to the dimensions of CE as well as their apparent relevance across the stages of construction. In total, the chapter evaluates 12 of the most relevant actors. The research will go over each of the actors one by one assigning them first to the Dimensions of CE based on their perceived interests and the phases of construction based on their relevance during at a specific time of the construction projects lifecycle. An explanation is provided for each of the relations. The chapter is finalized by giving a visual overview of the categorization in table 14.

Project owners – These are, generally, financially motivated actors that look for economic viability and the rate of returns of their investments on the construction projects. They are the primary stakeholders providing and overseeing the budget. While these actors, depending on their personal values, could also be tied to the "*Environmental"* category in case of commitments to reducing pollution or "*Societal"* category looking at their image, Project owners are primarily "*Economic"* actors. Looking at the temporal considerations of the categorization, these actors possess generally high power across the entire lifecycle of the construction practice only having to comply to the governmental regulations. Due to the fact that project owners tend to be the first actor of the construction practice while initiating the projects, their power could be considered to be highest at the "*Design phase".*

Governance actors – These are the important stakeholders that set the rules and regulations for the entire construction industry. Their primary influence lies in the "*Governmental/Policy"* dimension. Additionally, they possess the ability to address the "*Economic"* factors of the industry through subsidies and taxes as well as "*Societal"* factors with the promotion of CE principles and funding research, and "*Environmental"* factors through setting and enforcing goals. Due to their high importance, governance actors are tied with most dimensions of CE as well as "*All phases"* of construction as their policies need to be followed at all times.

Financial actors – These are the stakeholders such as banks that ensure financing of the construction projects. As suggested by the name, they are primarily concerned with "*Economic"* dimension of construction practice looking to make profit. Financial actors can be tied to many phases of construction, as they get involved if they see opportunities for making profit, but they are primarily involved during the "*Design phase"* as they generally provide the funding for the projects at the start and expect the returns on their investments later on.

Project managers – these are the actors tasked with overseeing the construction projects and ensuring it remains withing the given scope, budget, and are completed in accordance with the given time. At core they provide their services for monetary gain looking at the "*Economic"* dimension, but these stakeholders generally possess a central role in the construction team and are directly involved in communication and collaboration with many other actors tying them to the "*Societal"* dimension of construction practice as well. In general, project managers are involved during the "*Construction"* phase of the projects but depending on the types of collaboration and contractual agreements they can become a part of the team as early as at the "*Design phase"* up until and including the "*End of life phase".*

The design team – these are the actors in charge of developing sufficient architectural and engineering documents for the construction projects. They provide their services for a monetary gain and can thus be associated to the "*Economic"* category but depending on the personal values they could also be tied to "*Societal"* and *"Environmental"* dimensions. Looking at the time of their involvement in the project, their work is primarily completed during the "*Design phase"* when developing sufficient documents for the construction design.

Users – These are the primary actors that occupy the construction projects. They could range from User-owners to simple renters giving options for their categorization. In general, Users are "*Economic"* actors looking for high quality products for low value but depending on their personal values they could also be assigned to the "*Environmental"* dimension. Looking at their involvement, these actors are mainly considered during the "*Operation phase"* of construction projects.

Manufacturers – These are specialized actors overseeing the production of construction components and materials. They generally provide the goods for a monetary gain tying them to the "*Economic"* dimension but their involvement in the construction supply chain also gives them ties to the

"*Societal"* dimension due to their communication and collaboration with the other stakeholders. Additionally, they directly oversee the manufacturing process putting them in charge of the "*Technological"* aspects of the production. In terms of their time of involvement, they possess the highest level of relevance during "*Manufacturing and supply phase",* while also being involved during "*Construction phase"* and "*End of life phase"*.

Material suppliers – These are specialized actors in charge of providing high quality construction materials. At the core they are "*Economically"* motivated stakeholders providing their services for a monetary gain but depending on their practice they could be also tied to the "*Environmental"* and "*Societal"* dimensions, raising awareness about CE by working with secondary materials. Additionally, due to these actors' responsibilities they oversee the production of materials relating them to the "*Technological*" dimension of CE as well. In terms of their time of involvement, material suppliers are primarily to be considered during "*Manufacture and supply phase", "Construction phase" and* "*End of life phase".*

Environmental experts – These are the consultant actors providing their expertise to increase environmental considerations. They are directly tied to the "*Environmental"* dimension but due to them sharing their expertise and raising awareness about the topic of CE, these actors are also tied with the "*Societal"* category. Environmental actors could be a part of the project during all phases of construction, but they possess the highest impact during the "*Design phase"* as this is the time when the most influential decisions are made.

Sub-contractors – these are the common actors that conduct the simple and specialized tasks necessary for construction practice. They are mainly involved during the "*Construction phase*" but could also conduct the necessary activities during "*Operational phase*" and "*End of life phase*". In terms of the categorization based on dimensions of CE, sub-contractors' primary interest is "*Economic"* in getting paid for the work that they do but depending on personal interests they also possess the ability to influence "*Environmental"* factors as well.

Demolition operators – These are the common "*End of life phase"* actors the conduct the activities related to the deconstruction and demolition of the construction projects. In simple terms they can be viewed as "*Economic"* actors working for profit, but the nature of the work done by these stakeholders also ties them to the "*Environmental"* dimension. In more circular projects, such EOL actors can be seen involved at the "*Design phase"* of the construction projects as well.

Resource storage and logistics actors – These are specialized actors that provide facilities for storing construction materials and are relevant for optimizing logistics of the construction practice. Resource storage and logistics actors are versatile in terms of their involvement appearing during "*Manufacturing and supply", "Construction",* and "*End of life"* phases. While providing simple services they can address "*Economic", "Societal"*, and "*Environmental"* factors by being connected to many stakeholders and increasing options for logistic operations and availability of environmentally friendly solutions.

Looking at the general trends, it can be observed that various stakeholders can be seen tied to more than one category based on both dimensions of CE and phases of construction, but in they mainly have a primary connection, for example project owners are primarily interested in "Economic" aspects but have the capacity to be involved into more things. Additionally, Governance actors seem to have the largest number of interconnections due to their central role in shaping the context of the world where the construction projects are designed. The table below summarizes the categorization conducted in the chapter. In the case of the stakeholders' connection to multiple categories, the given variable in **bold letters** shows the most relevant ones.

Table 14. Categorization of the important actors of the construction industry.

Stakeholder	Dimension of CE	Phase of construction
Project owner	**Economic,** Environmental, Societal	**Design phase,** all phases
Governance actors	**Governance/Policy,** Environmental, Societal, Economic	All phases
Financial actors	**Economic**	**Design phase**, All phases
Project management actors	**Societal,** Economic	**Construction phase**, All phases
The design team	**Economic,** Societal, Environmental	Design phase
Users	**Economic**, Environmental	Operational phase
Manufacturers	Economic, Societal, **Technological**	**Manufacturing and supply**, Construction phase, End of life phase
Material suppliers	Environmental, Economic, Societal, **Technological**	**Manufacturing and supply,** Construction phase, End of life phase
Environmental experts	**Environmental,** Societal	**Design phase**, All phases
Sub-Contractors	**Economic,** Environmental	**Construction phase,** Operation phase, End of Life phase
Demolition operators	**Economic,** Environmental	**End of life phase**, Design phase
Resource storage and logistics actors	**Economic**, Societal, Environmental	**Manufacturing and supply**, Construction phase, End of life phase

With the completion of categorization of the relevant barriers, the report has all the necessary information to explore relationships between actors, barriers, and enablers to identify pathways that can be used to strategically combat problems of the construction industry.

7.4 Basic approach to developing solutions

This chapter presents the general approach that will be used to evaluate each of the barriers. This approach is created to guarantee a more structured set of strategies that analyzes each of the barriers in the same manner and ensures consistency. Moreover, it guarantees the quality and the effectiveness of all the solutions by ensuring that each solution utilizes information about all key aspects such as data about barriers, enablers, and stakeholders. Finally, the predefined approach ensures that it is not necessary to start from noting for each barrier, instead it is possible to save time by simply applying the available methodology to all solutions.

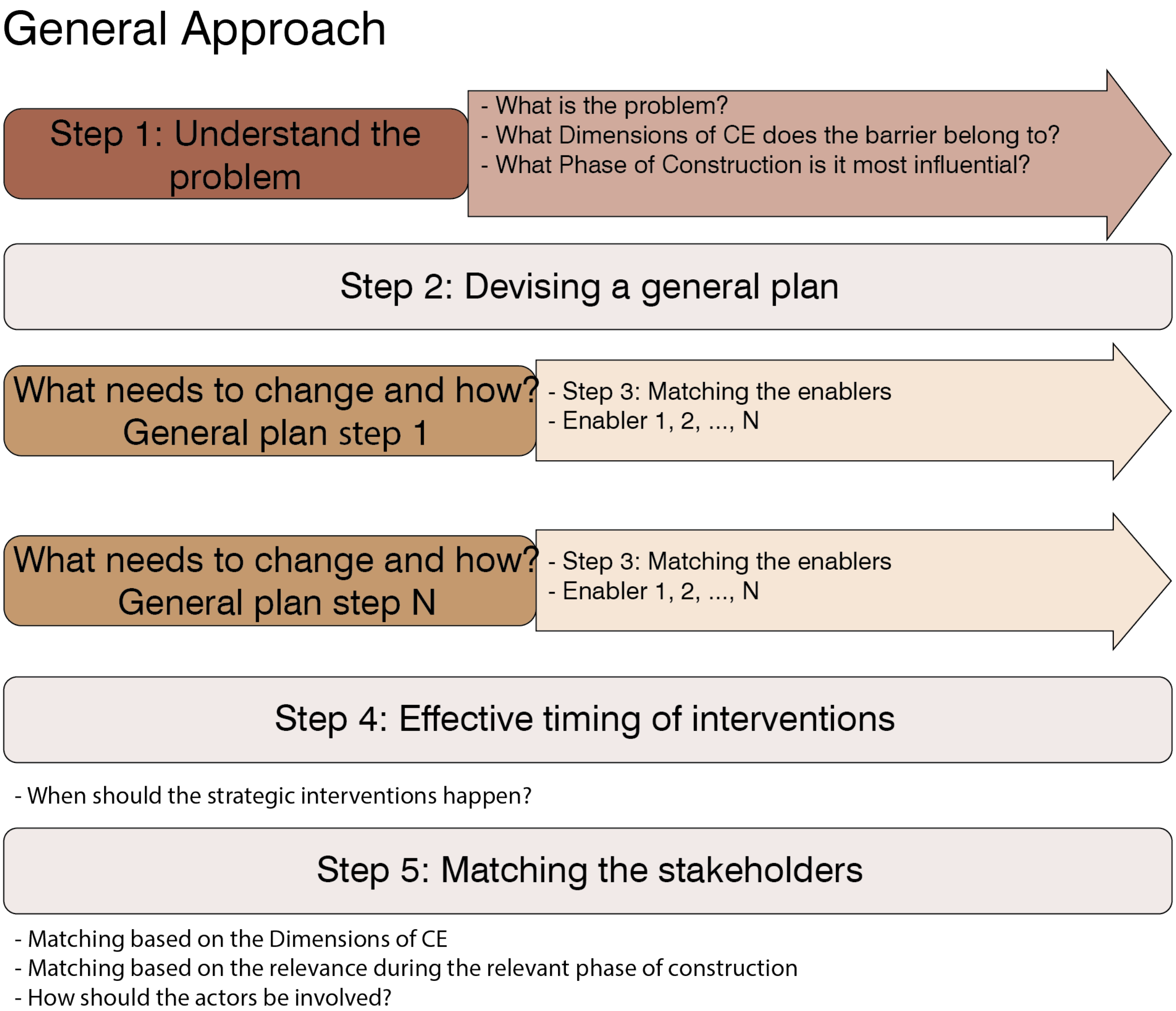


Figure 9. Five step process to developing strategic interventions for each barrier

Step 1: Understand the problem

The first step of identifying a solution is ensuring an in-depth understanding of the problem at hand. This ensures that the devised strategies are relevant and targeted, not wasting efforts on irrelevant approaches and utilizing all the available resources to achieve the final goal.

During this step, it is necessary to ask, “what is the problem?” looking at the core of the issue and the way it prevents CE adoption. Next it is important to know when the problem appears, looking at the category of “Phase of construction” and finally, how does the barrier affect the construction industry, evaluating based on the category of “Dimension of CE”. Answering all the given questions ensures that the strategic approach takes into account all the available relevant information for each of the barriers.

Step 2: Devising a general plan

After answering all the questions in step one, it is time to look for the primary activities that need to be altered to address the core of the barrier. This step doesn't require in-depth solutions, it only seeks to answer: "what needs to change?" and "how can this happen?". These questions are directly tied to the previous step and together they paint a simple future where the barrier is solved. It is important to note that some barriers could result in more than one solution and all of them need to be considered in unison.

Step 3: Match the enablers

With the knowledge about the things that need to be changed, step 3 looks into the available strengths and opportunities that can be used to address the root causes of the barrier. Using the categorized information, it is possible to match enablers with specific barriers, ensuring that each of them affect the same dimension of CE and are effective during the same phase of construction. It is important to note that the categorization of barriers showed that the issues were often related to many if not all phases of the construction lifecycle, thus the dimensions of CE will likely be more effective for matching enablers with barriers.

The selected enablers can be matched with the devised general plan from step 2 to show what opportunities can be leveraged and used in the strategies. Figure xxx shows the approach taken during the first three steps.

Step 4: Effective timing of interventions

With the general strategy in place, it is important to determine the most optimal times for interventions. During this step the strategy must answer the question: "when should the strategic interventions happen?" by looking at the category of most important phases of construction for both barriers and enablers. The given information shows the effectiveness of enablers as well as the impact of the barriers during each stage of the construction project's lifecycle. The most relevant times need to be selected for interventions.

Step 5: Matching the stakeholders

Finally, the strategy needs to tie the key stakeholders to the solutions by looking at their interests, responsibilities, and influence over the projects during the effective times of interventions. The general strategy and the "Dimensions of CE" of selected barriers and enablers allows for identifying which actors are needed for implementation. Moreover, with the knowledge about the effective timing of solutions, it is possible to define when the stakeholders need to be involved and how much influence they have over the project. Figure 10 shows the final two steps of strategy development.

Combining all the given information, the report creates basic plans for stakeholder engagement showing who to interact with and how in order to ensure practical applications of the strategies.

This five-step sequence gives a simple approach for devising solutions for each of the key barriers and it will be used for developing 10 basic strategies in the following chapter.

7.5 Preliminary strategies

This chapter provides the culminating synthesis of all the research gathered in the report to give a complete answer to SQ5: *"What is the relationship between the barriers, enablers, and the actors of the construction industry and how can these connections be utilized to accelerate the industry wide transition? ".* Chapters 7.1 to 7.3 have categorized all of the explored variables to simplify the process of identifying interconnections. Now, these findings are used to seek interrelations between the explored variables to give a comprehensive, barrier specific, interventions as a main deliverable of the research to develop strategies for accelerating industry wide transition into a circular mode of operation in accordance with the general approach given in chapter 7.4.

Unclear financial case

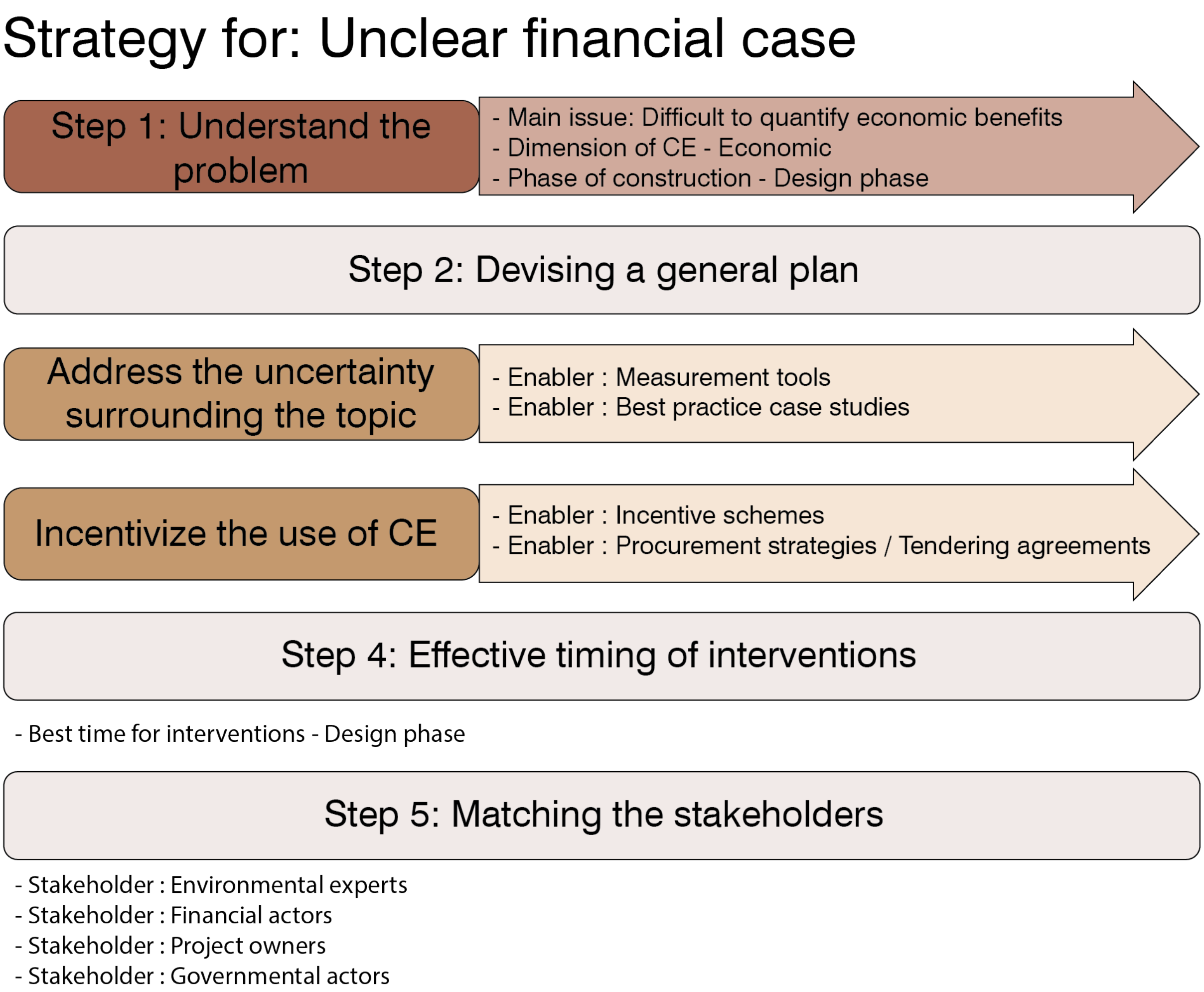


Figure 10. Strategy for the barrier Unclear financial case

Step one – understanding the problem: The report has identified this to be the most influential barrier that needed to be prioritized by the strategies. The barrier stems from the difficulty of quantifying its economic benefits, which creates uncertainty about the topic, deterring potential financial investors. Looking at the "Dimensions of CE", this barrier is tied to the "*Economic*" dimension due to the uncertainties surrounding its financial viability. Moreover, the barrier can be seen tied to all phases of construction, but its relevance was perceived to be the highest during the "*Design phase*".

Step two – Devising the general plan: In the case of the given barrier, it is necessary to 1. Address the uncertainty surrounding the topic by demonstrating its financial viability to make it more clear why is it beneficial to commit to circular operations and 2. Incentivize the use of CE to make it more attractive to invest in this new way of operation. These two steps address the primary issues of the barrier discussed during the first step.

Step three – Matching the enablers: This step matches the appropriate enablers to the previously devised steps of the general strategy. Looking at the first problem, in order to get rid of the uncertainties surrounding the topic of CE, it is necessary to utilize the strengths and enablers of the concept that demonstrates its financial viability and allows for better quantification of the future gains. Additionally, the utilized enablers should be tied with the "*Economic"* dimension of CE as this is the primary category of the addressed barrier. The two primary enablers that fit this category are as follows:

Measurement tools – This enabler promotes development and use of tools such as Life Cycle Assessment (LCA) to quantify the environmental and economic impact of the projects. The power of this tool can be seen demonstrated in the research of Fregonara et al, (2017) where LCA is used to compare the financial viability of two alternative materials for construction based on various variables such as Embodied Energy and Embodied Carbon.

Best practice case studies – This enabler advocates for additional research surrounding the topic of CE through real-life applications to demonstrate the economic and environmental feasibility of adopting the new way of operation. This approach allows the industry to document the successful projects and identify the factors leading to their success.

After addressing the issues surrounding the uncertainty of the CE concept, the strategy looks for the enablers that help in incentivizing the industry for using this way of operation. Enablers "Incentive schemes" and "Procurement strategies / Tendering agreements" can greatly help with addressing this problem. Incentives can be seen in the form of the subsidies or tax breaks to reduce the initial costs making CE initiatives more attractive, while procurement strategies can prioritize circular principles to increase the demand for new projects, making it more attractive to commit to them.

Step four – Timing of the interventions: After selecting the appropriate barriers, it is time to look for the effective timing of interventions. All the used enablers as well as the main barrier have been tied to the "*Design phase"* of construction which suggests the need for interventions at the early stages.

Step five – Matching the stakeholders: Finally, the strategy can look to developing stakeholder intervention plans by looking for appropriate actors based on their impact over construction projects as well as the dimensions of CE. While approaching the actors the most notable stakeholders that could assist in resolving the previously described issues are the "Environmental experts" as they possess the sufficient knowledge to educate the industry about the long-term benefits of CE and reduce the uncertainty around the subject. The other relevant actors during this stage include "Project owners" and "Financial actors". These stakeholders need to be educated about the benefits of CE to reduce the uncertainty and show them the potential benefits. Besides the actors tied to the "Design phase", the "Governmental actors" have a key role in guaranteeing the success of the circular projects as they are directly in charge of giving overarching policies, regulations, and incentives that influences the perceptions and interests of the entire construction industry. To accelerate the transition to the circular construction industry, it is necessary to connect highly influential actors such as "Governance actors" with highly knowledgeable "Environmental experts" to develop most complete policy interventions.

Unclear policy support

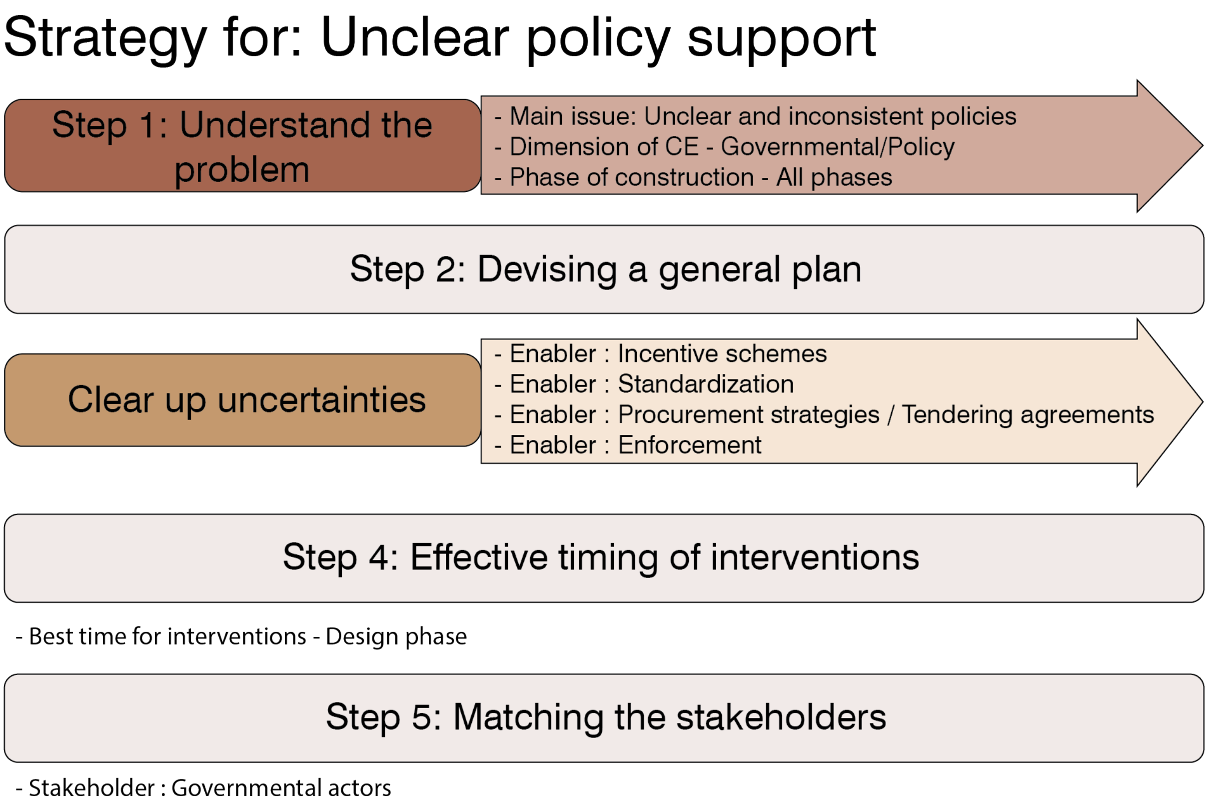


Figure 11. Strategy for the barrier Unclear policy support

Step one – understanding the problem: Unclear policy support was found to be one of the highest priority barriers to overcome in this research. This hurdle refers to the problematic nature of lack of clarity and consistency in the governmental policies and regulations that are meant to incentivize CE practice within the construction industry. This ambiguity creates uncertainty and hesitancy in the sector as the lack of strong policy signals gives the perception that there is no urgency or need for change slowing down the transition.

This is a highly complex barrier that was tied to multitude of "Dimensions of CE" with the strongest correlation to the "*Governmental/Policy*" side. In terms of the time when this barrier appears to be most relevant, categorization has tied it to "*all the phases*" of construction showing the complexity and severity of this issue.

Step two – Devising the general plan: To address the root causes of this problem, it is necessary to clear up uncertainties and hesitancy in the industry to committing to the circular practices through the development of clear, consistent, CE specific policies that are designed to nudge the supply chain in the desired direction.

Step three – Matching the enablers: The barrier was seen to be tied to all the "Dimensions of CE" but has shown greater correlation to the "*Governmental/Policy*" category. This implies the enablers under all categories possess the ability to influence the given problem but the opportunities under

"*Governmental/Policy*" category are expected to be the most effective. The following four enablers are expected to be the most appropriate for resolving "Unclear policy support":

Incentive schemes – It is possible to create policies and incentives that offer tax breaks, subsidies, and grants for construction projects that comply with the CE principles. These policy interventions create clear incentives for the use of the new construction practices avoiding ambiguity. Additionally, it is possible to promote the use of secondary materials by developing financial incentives for their use. While this approach is extremely simple, this is its primary benefit as it is impossible to confuse their intention to provide clarity to the industry.

Standardization – CE operations require a significant shift from the traditional practice, which can be clearly seen in the case of the use of secondary materials, as there are no clear processes that can be followed for the reuse of construction components and reclaimed resources. By developing standardized criteria and methodology for assessing both materials and the processes it is possible to define clear steps that can or cannot be followed. The standardization processes can be observed in the case of the enabler material passports and databases or certification of secondary resources.

Procurement strategies / Tendering agreements – Tendering agreements that prioritize the use of CE products, services, and procedures can be prioritized in the case of public procurements, showing the preferred mode of operation and increasing the number of large-scale projects that can be used as case studies or successful examples.

Enforcement – while this was not an identified enabler, it is clear that there are various CE based policies already in Europe and all over the world seen in the examples of Japan in 2002 with the introduction of "Basic Law for Establishing a Recycling-Based Society", China in 2009 "Circular Economy Promotion Law of the People's Republic of China", EUs 2015 Circular Economy Strategy (Geissdoerfer et al., 2017). Despite the limitations and problems related to the already established frameworks, it is not reasonable for the construction industry to simply ignore the existence of such large documents. Without strong enforcement of the established CE goals, there is no perception of urgency or the need for compliance. It would be advisable for the governments to start enforcing the already present goals to clarify their intentions in the construction sector.

Step four – Timing of the interventions: Looking at the appropriate timing for interventions, the barrier doesn't show specific phase of construction where it is the most impactful, but the selected enablers such as "Incentive schemes" and "Procurement strategies / Tendering agreements" greatly benefit from early interventions making the "*Design phase*" the most influential.

Step five – Matching the stakeholders: The last variable of the strategies is the stakeholder part. In the case of the barrier "Lack of clear policies", despite its relation to many dimensions of CE and phases of construction, it is easy to identify that the "Governmental actors" most relevant when overcoming this issue. It is necessary to engage in active dialogue and collaboration with these stakeholders to advocate for the development and implementation of effective CE policies and regulations.

High upfront adoption costs

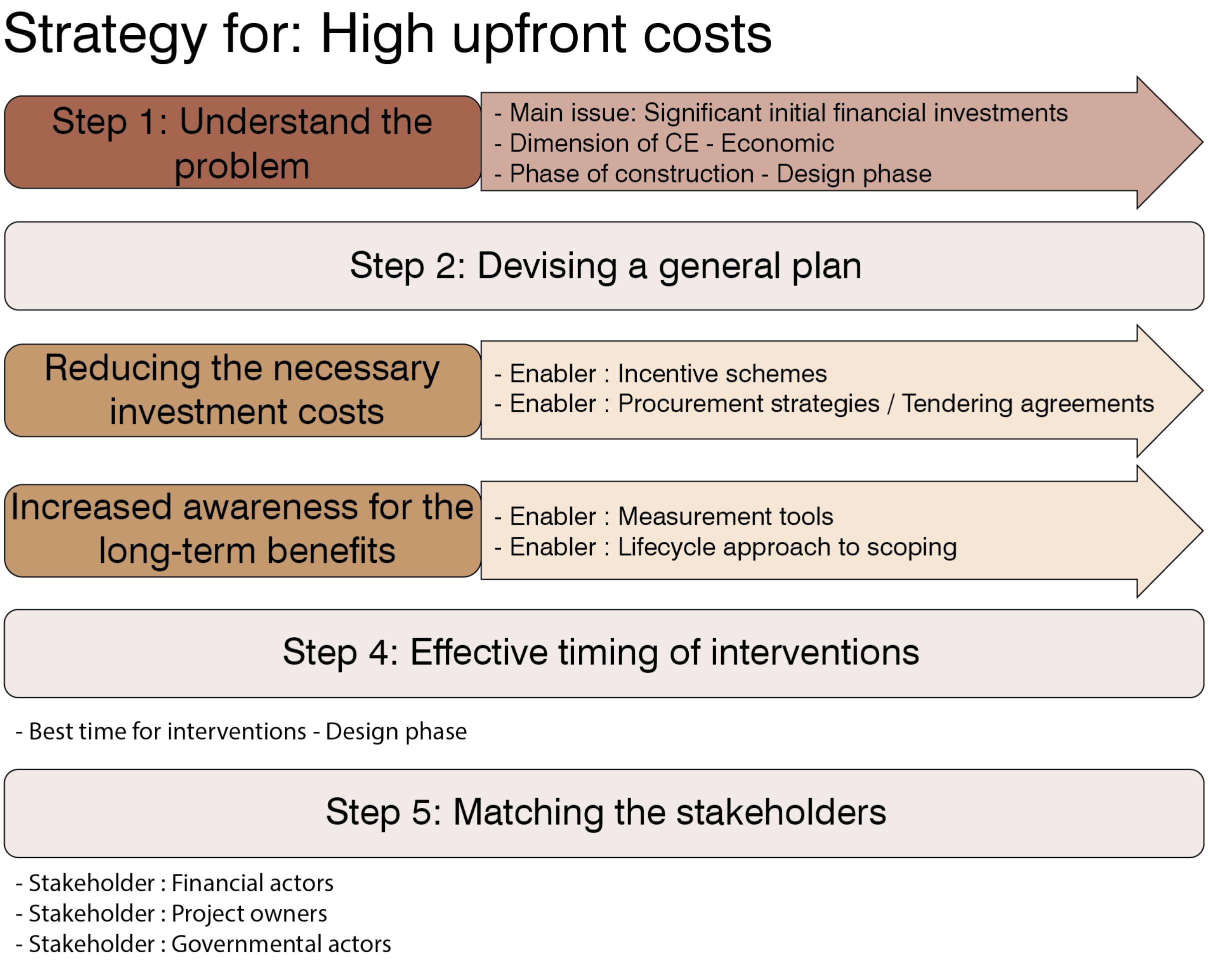


Figure 12. Strategy for the barrier High upfront costs

Step one – understanding the problem: This is the last of the barriers that were under the high priority category. High upfront adoption costs refer to the significant initial financial investments necessary for implementing new, circular mode of operation in the construction practice due to the associated costs with: New technologies, new infrastructure, research, training highly skilled personnel, EOL procedures. Such necessary financial commitments act as a deterrent to many actors in the industry, preventing its widespread adoption. These issues are exacerbated by the uncertainty around the financial returns and lack of established processes for CE operation such as material reuse.

The barrier belongs primarily to the "*Economic*" dimension of CE and is most prevalent during the "*Design phase*" of the construction.

Step two – Devising the general plan: The primary approach to resolving this issue should focus on 1. Reducing the necessary investment costs for circular operations to clarify the financial benefits of circular operations and 2. Increased awareness for the long-term benefits associated with CE, shifting from the focus on short term financial returns.

Step three – Matching the enablers: The strategies should utilize the enablers under the "*Economic*" category for maximal success due to the nature of the addressed barrier. While attempting the lower the initial load of financial commitments, the report has identified the following two enablers that could help in achieving this end:

Incentive schemes – in order to offset the high initial costs related to adopting the circular practice, it is possible to look into economic policy interventions. This can be approached in various ways. First, it is possible to provide funding for the research and development of circular processes and materials to limit the financial demand of developing new solutions. Additionally, it is useful to establish funds dedicated specifically to supporting CE projects, lowering their initial costs. Finally, the governmental grants, subsidies, and tax breaks further lower the economic burden on the circular projects.

Procurement strategies / Tendering agreements – Establishing green procurement procedures that priorities projects utilizing CE principles and services in regular and public procurements will influence the perception of circular products, increase demand and provide reasons for justifying investments into such projects.

Moving onto the second part of the strategies, it is beneficial to establish the long-term benefits of incorporating CE principles in the construction practice. This approach requires a well-defined business case as well as the general shift of the sector away from the short-term profits. The following enablers provide the tool for developing such strategies:

Measurement tools - This enabler gives opportunities for quantifying the environmental and economic impact of the projects. It utilizes tools such as LCA to translate the general benefits of CE practice into financial terms allowing for a clear business case. Through use of this enabler, it is possible to commit to the new practice due to the demonstrative examples of the future gains.

– This is a necessary enabler touching upon "*Economic*" dimension of CE, where it recognizes the short-term focus of the industry about the profits (Adams et al., 2017) and advocating for the need for more patient outlook on the Rate of Return (ROI) on investments. With the overview of the bigger picture, the industry might be less hesitant to adopt these options.

Step four – Timing of the interventions: The given barrier as well as majority of the selected enablers are strongly tied to the "*Design phase"* of the construction practice, thus interventions during this time are likely to be most effective.

Step five – Matching the stakeholders: Due to the effectiveness of interventions during the "*Design phase"*, it is logical to involve the actors that possess the higher relevance at this time while also being related to the "*Economic*" dimension and possessing sufficient tools to impact implementation of the suggested strategies. Governmental actors possess relevance during all stages of construction and are in the best spot for impacting "Incentive schemes" and "Procurement strategies". The construction projects should work closely with these stakeholders while developing effective strategies. Additionally, "*Financial actors*" and "P*roject owners*" should be kept informed and educated about the topics of CE as they dictate the initiation and the budget of the projects and should be convinced about the benefits of operating in a circular manner.

Lack of knowledge/expertise about CE

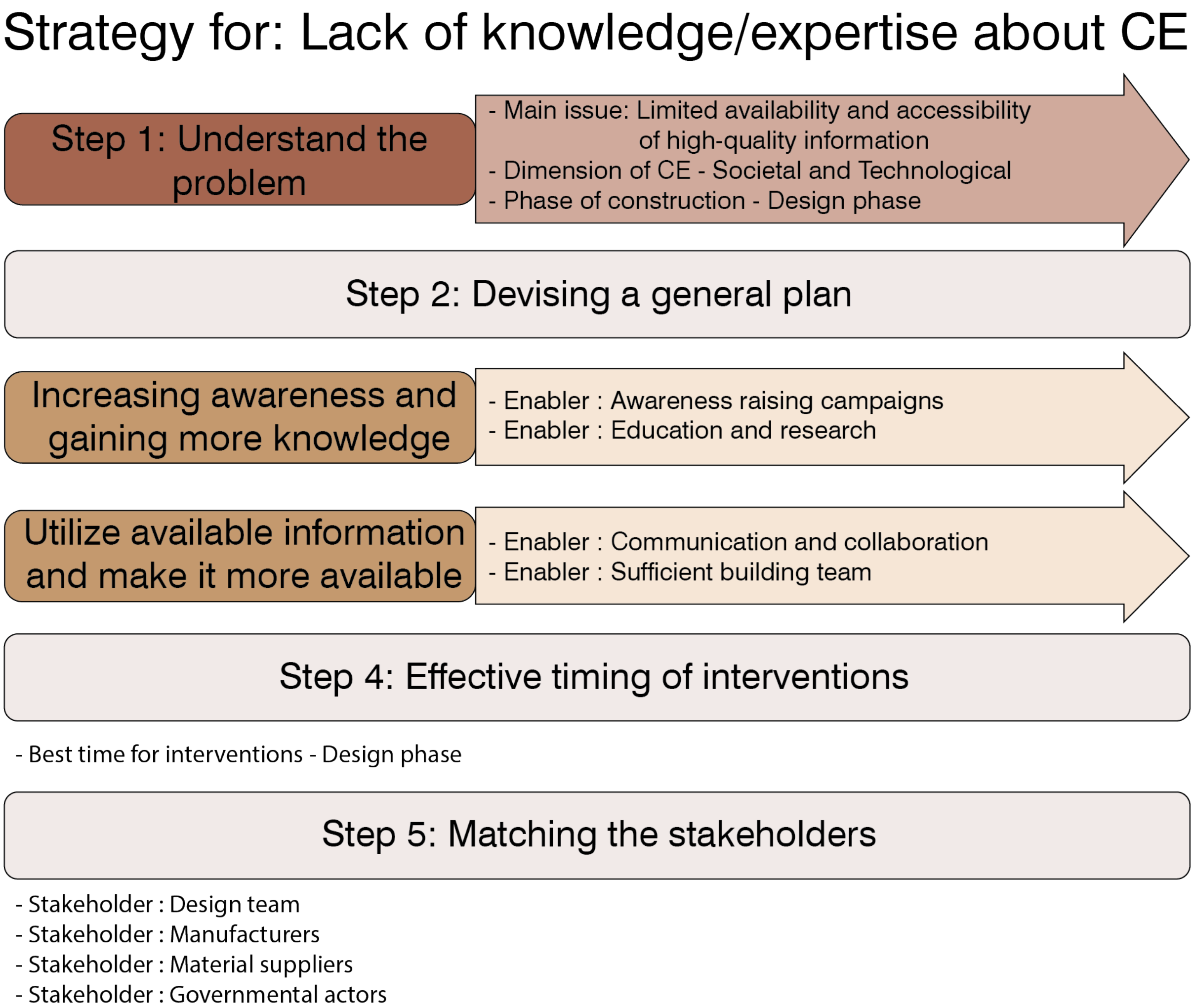


Figure 13. Strategy for the barrier Lack of knowledge/Expertise about CE

Step one – understanding the problem: The lack of knowledge and expertise about the topic of CE in the construction industry was given medium-high relevance just below the high-priority issues. This barrier stems from the limited availability and accessibility of high-quality information regarding the topic resulting in the lack of awareness in the construction sector. The problem is further exacerbated by the lack of practical applications, further reducing the available knowledge base and making the topic less understood. These issues hinder the adoption of CE practices by creating uncertainty and hesitancy about the topic, leading to fragmented approach, reluctance to depart from traditional operations, and missed opportunities.

Looking at the categorization of this barrier, it can be seen to have strong ties to the "*Societal*" and "*Technological*" dimensions which on one hand speaks about the limited awareness of the topic of CE while also suggesting the lack of available knowledge. Additionally, the issue remains highly relevant across the entire lifecycle of construction but is perceived to be most impactful during the "*Design phase*".

Step two – Devising the general plan: The primary approach for addressing this barrier should include strategies for increasing awareness, gaining more knowledge through research, and demonstrating its viability through pilot projects to allow the practitioners to operate in circular manner.

Step three – Matching the enablers: "*Societal"* and "*Technological"* enablers are likely to be most influential while addressing this problem. While looking to increase the quality and availability of information about CE principles, the research has identified following enablers to be most appropriate:

Awareness raising campaigns – It is necessary to make the construction practitioners more aware of the availability and benefits of CE principles. To combat this problem, it is necessary to pay more attention to the universities and schools to educate future practitioners about the CE concept. Moreover, the current practitioners can be made more aware through workshops and seminars as well as mentorship programs as suggested by the research of (Lee et al., 2023).

Education and research – Besides spreading the available knowledge, it is influential to invest into further research about circular materials, technologies, and methods prioritizing the practical solutions to close the gap between research and practice. More specifically, developments around the topic of evaluation could lead to increased perception and less uncertainty around the topic of CE which would help in building a stronger business case and attracting investors.

While it is necessary to gain more insights about circular projects through additional research, it is also necessary to utilize the available resources and expertise in the supply chain addressing the "*Societal"* side of the barrier. It is noticeable that the limited expertise often can be tied to the lack of circular projects as well as limited information sharing. These are very fundamental problems observable in the construction sector, which is composed of very isolated, self-interested stakeholders. The primary enablers to combat these challenges are:

Communication and collaboration – These are simple enablers that encourage the actors of construction to be more open to sharing information and working together towards the same goal utilizing the strengths of each stakeholder. A collaborative approach was seen as an essential factor for comprehensive solutions and is thus a necessary step towards a circular construction industry.

Sufficient building team – It is important to select the right actors for the construction projects considering all aspects of expertise, reputation, and attitude towards CE. Selection of the "right team" simplifies goal alignment, promotes accountability, and helps with increased communication and collaboration.

Step four – Timing of the interventions: Similar to the other barriers, "Lack of knowledge/expertise about CE" can be tied to all phases of the construction practice, but the problem is more challenging to deal with if it is apparent during the early stages. Similarly, the selected enablers can be seen to be tied to the "*Design phase"* and thus interventions should be made at this time.

Step five – Matching the stakeholders: "Governmental actors" possess the highest influence over the project across the entire lifecycle and are in a great position to promote additional research and raise awareness in the supply chain. Additionally, the actor "design team" directly relates to the last proposed enabler and shows the importance of working with the right people. Moreover, the specialized expertise of actors such as "manufacturers", "material suppliers", and "environmental experts" should be used to raise awareness about the topic of CE.

Fragmented supply chain

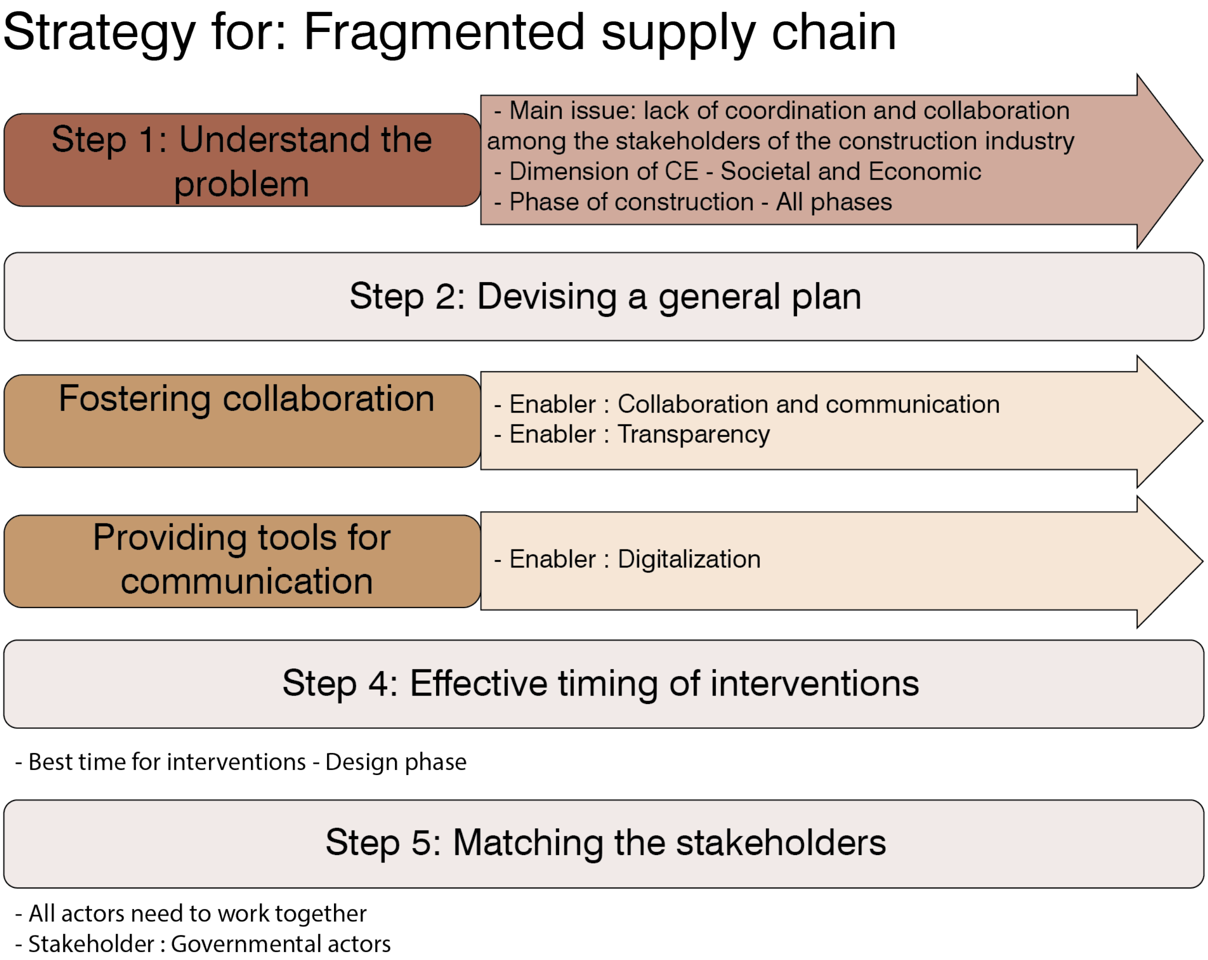


Figure 14. Strategy for the barrier Fragmented supply chain

Step one – understanding the problem: This barrier refers to the issues arising from the lack of coordination and collaboration among the stakeholders of the construction industry with each actor aiming for only personal gains. Such a supply chain is defined by independently acting actors, limited information exchange, lack of comprehensive approaches, limited integration between forward and backward logistics, and lack of general trust and accountability. This poses a significant barrier to the adoption of CE slowing integration of circular principles, missing available opportunities, and reducing the effectiveness of CE initiatives due to the lack of integrated, holistic approaches.

The given list of issues was categorized to have strongest ties to the "*Societal*" and "*Economic*" dimensions of CE due to the problems arising due to the interpersonal relationships, or the lack there of, between the actors of the construction industry as well as their economic motivations. This is a complex barrier that is difficult to tie to any particular phase of construction but, the previously found general approach states that interventions during early stages tend to be most relevant.

Step two – Devising the general plan: The primary challenges of this barrier can be addressed through fostering communication, collaboration, and integration across the entire supply chain to allow for opportunities for information sharing, accountability, and holistic interventions.

Step three – Matching the enablers: The enablers under the "*Economic*", and "*Societal*" categories possess the greatest potential for addressing the challenges. The following enablers have been selected to best match the barrier of fragmented supply chain:

Collaboration and communication – Increased collaboration and communication among the actors will directly resolve many of the issues of the fragmentation of the supply chain. To successfully apply this enabler, it would be recommended to create an environment in the construction industry that fosters communication through established networks for information exchange, platforms for multistakeholder connections, and collaborative contractual agreements that promote shared goals and responsibilities (Zvirgzdins et al., 2019) (Eberhardt et al., 2020).

Transparency – To increase communication and collaboration between the actors it is necessary to address the limited trust between them. The general trust among the practitioners promotes accountability and ensures a positive attitude towards the shared goals of the project. To increase trust it is useful to look into various technologies such as Block chain that increases traceability and transparency of the documents which allows for better accountability among the practitioners (Elghaish et al., 2023).

– With the available tools it is possible to transfer all of the necessary construction files in a digital world utilizing the tools such as digital twin, BIM, and Block chain to increase the productivity and promote transparency among the actors. Digitized tools improve data management opportunities and allow for new strategies such as material tracking.

Step four – Timing of the interventions: The complex nature of the barrier makes it difficult to pinpoint the exact timing of intervention that would increase their effectiveness, but categorization of enablers, as well as the general approach imply that the "*Design phase*" is the most optimal time for action.

Step five – Matching the stakeholders: The fragmented supply chain involves all the actors of the construction industry and thus it is necessary to collaboratively approach this problem with all relevant stakeholders. The need for an overarching approach can also be viewed with the suggested enablers with them being tied to all phases of the construction industry. While it is clear that the entire supply chain needs to work together to resolve the issues, "governmental actors" generally possess the highest power to nudge the sector in the desired direction and it is recommended to work with this stakeholder when implementing the strategy.

Lack of mechanisms for material recovery

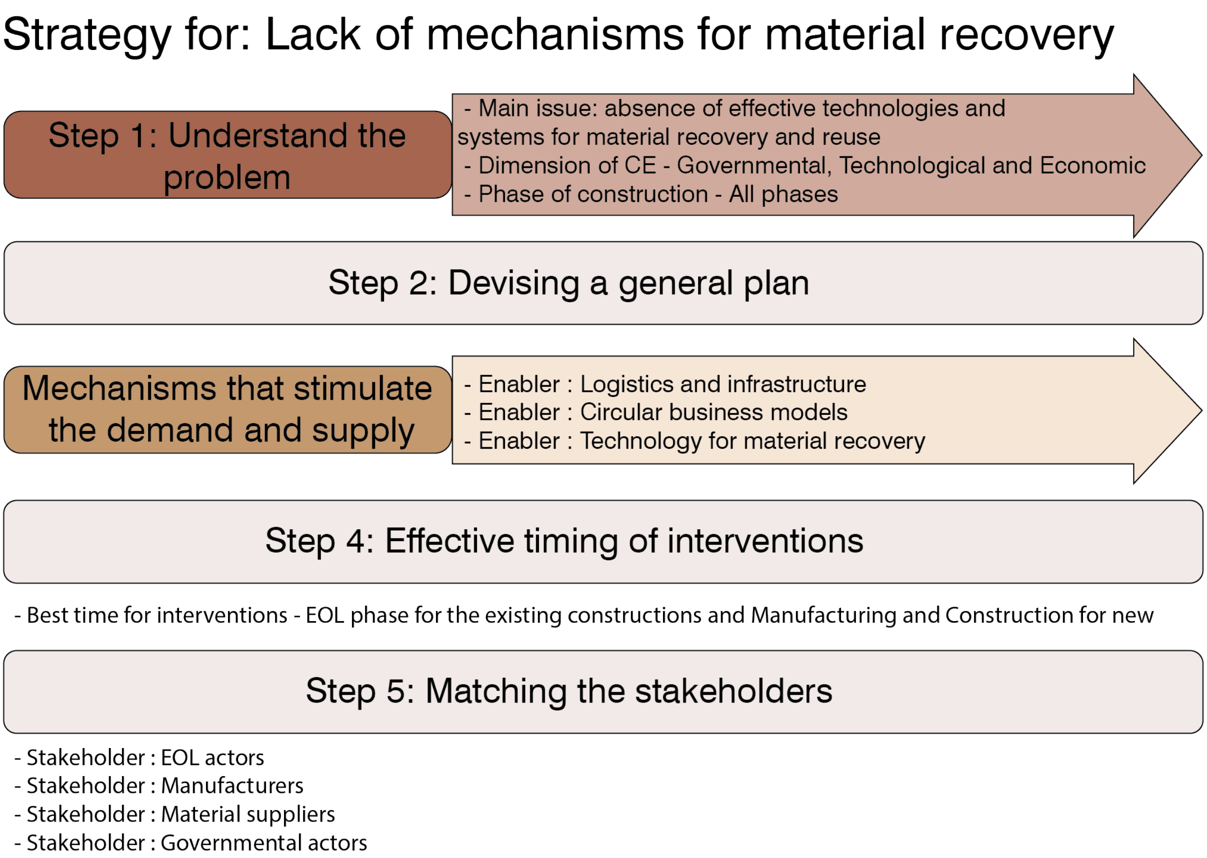


Figure 15. Strategy for the barrier Lack of mechanisms for material recovery

Step one – understanding the problem: This is a multifaceted barrier that, at its core, refers to the absence of effective technologies, infrastructure, and systems that enable recovery and reuse of construction materials in the industry. Additionally, this barrier stresses the problems coming from the non-existent markets for secondary construction materials, limited distribution points, and the preference towards use of virgin materials (AlJaber et al., 2023). These issues together reduce the economic viability of circular projects, hinder reuse and recycling of materials, and reduce the incentives for construction companies to engage in circular practice.

The problem touches upon many dimensions of CE but has the strongest ties to the "*Governmental/policy*", "E*conomic*", and "*Technological*" dimensions. Additionally, the categorization advised against limiting this issue to a singular phase of construction as its relevance can be seen throughout the entire lifecycle.

Step two – Devising the general plan: The solution requires strategies that create mechanisms that stimulate the demand and supply of the secondary materials through establishing markets and economic systems that simplify the production, storage, and reuse of the secondary materials.

Step three – Matching the enablers: Due to the complexity of the given barrier, it is necessary to utilize the enablers under all the categories of *Governmental/policy*", "E*conomic*", and "*Technological*". These opportunities look at the solutions that provide additional systems and services in place to simplify material recovery. The report identifies following barriers as the potential resolutions for the primary problem:

Logistics and infrastructure – This enabler combines enablers of “sufficient infrastructure” and “optimized logistics”. It advocates for optimizing logistics of collection, transportation, and storage of reclaimed materials and establish collection points and systems that facilitate reuse of secondary goods. By providing more efficient tools and systems for circular operations the attractiveness of the concept increases having impact both on perception and economic viability. For the sake of conciseness, a more detailed description of the solutions are not included but can be found in the used articles given in table 11.

Circular business models – This enabler combines the previously defined strategies of “Ownership models”, “Take back schemes” and “Extended manufacturer responsibility”. These opportunities allow for more options for construction and materials at the EOL stage and involve new qualified actors to extend their effective lifecycle. Such a lifecycle-based approach incentivizes production of higher quality materials that are easier to maintain and recycle utilizing the expertise of most relevant stakeholders at crucial times.

Technology for material recovery – This is a purely “Technological” enabler that discusses the need for optimization in the procedures and the technologies for the activities at the EOL stage. Such an approach requires additional investments into research and case studies to create demonstratable results showing alternative approaches to EOL phase.

Step four – Timing of the interventions: As mentioned in the beginning, the barrier is not tied to any particular phase of construction and is relevant across the entire lifecycle. Conversely, the solutions show the strongest connections to the “EOL phase” followed by “Manufacturing” and “Consstruction”. This shows the necessity of actions at the later stages of the existing construction projects to establish systems that simplify use of secondary material for future projects.

Step five – Matching the stakeholders: The successful implementation of these strategies is reliant on utilizing the expertise and influence of the right actors at the right time. ms and infrastructure and incentivizing following new business models through policies. Additionally, “EOL actors” and “environmental experts” possess sufficient expertise to help develop effective systems for material recovery, thus they should be consulted while implementing strategies. Finally, “Manufacturers” and “Material suppliers” should be made aware of newly developed systems to implement secondary materials into their products.

Lack of interest

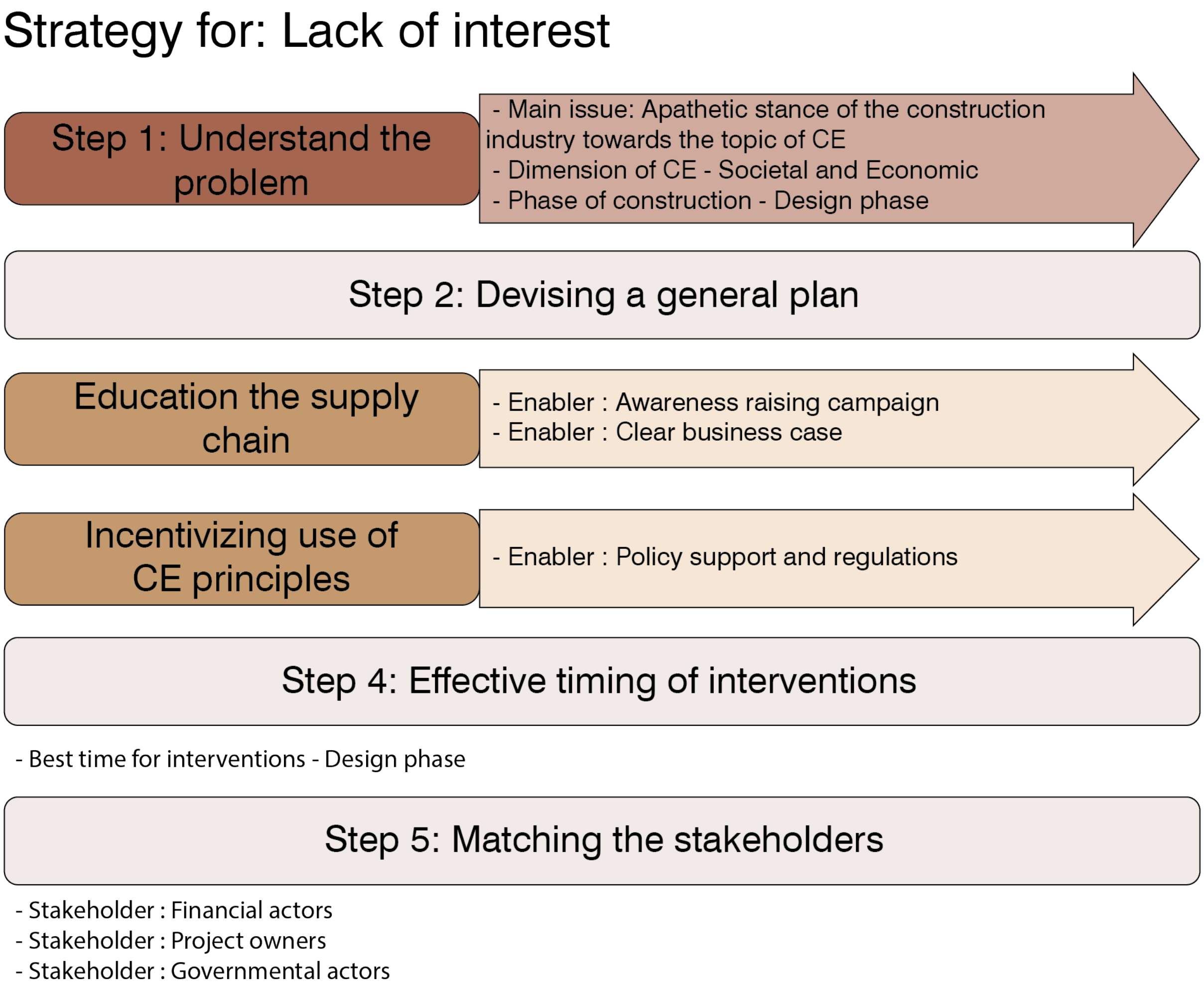


Figure 16. Strategy for the barrier Lack of interest

Step one – understanding the problem: This barrier concerns itself with the apathetic stance of the construction industry towards the topic of CE. It gets in the way of adoption of CE by hindering adoption of new technologies and processes essential for CE practice, creating resistance or lack of urgency to change complicating transition away from linear practice, and limits investments into circular operations due to the low perceived value.

At the core, it is a "Societal" barrier where the supply chain actors of construction are simply not aware of circular products or don't see the need to invest into them. Additionally, it can be tied to the "Economic" dimension as majority of the decisions made in the current construction industry are economically motivated, thus monetary interventions could change the perceptions. Finally, the barrier appears during all stages of construction but is most impactful during the "Design phase".

Step two – Devising the general plan: The primary problem that needs to be addressed is the limited awareness about the ways CE operates and its benefits, this can be done by educating the supply chain actors about the topic and incentivizing them to commit to circular practices.

Step three – Matching the enablers: The barrier can be addressed through "Societal" and "Economic" enablers as these categories match the closest to the problem. They need to highlight the benefits of CE emphasizing the long-term advantages and incentivize the actors to commit to this new way of operation. The following enablers were seen to fit the described criteria:

Awareness raising campaign – To combat lack of interest stemming from the limited knowledge and understanding of CE, it is advisable to educate society and raise their awareness of the benefits of the concept. This can be done through organizing industry events and conferences, developing training programs, and promoting public awareness through the media (Wielopolski & Bulthuis, 2022) (Lee et al., 2023).

Clear business case – The limited interest in circular solutions could be partially associated with lack of demonstrative case studies and general information showing the relevance of the concept. It is important to gather sufficient information by showcasing successful CE projects, promoting pilot projects, and developing real-world examples of the relevance and benefits of the topic.

Policy support and regulations – The limited interest can be altered by implementing attractive policies that provide subsidies and tax breaks for the use of circular projects. Additionally, policies could encourage the use of secondary materials and collaborative approach to construction showing clear benefits to the circular operations and increasing the interests.

Step four – Timing of the interventions: Looking at the temporal considerations of this strategy, the suggested interventions can be implemented at any stage of the construction practice, but their effectiveness increases during the earlier stages of construction such as "Design phase".

Step five – Matching the stakeholders: As in the case of other barriers, many stakeholders can and should be involved to develop effective strategic solutions. While looking to incentivize the actors, "Governmental actors" possess the greatest ability to navigate this process though policy interventions and awareness raising campaigns. Meanwhile, the highly influential actors at the design stage such as "Financial actors" and "Project owners" should be educated about and made aware of the long-term financial benefits of circular operations, to convince them to invest into practice.

Complexity of construction

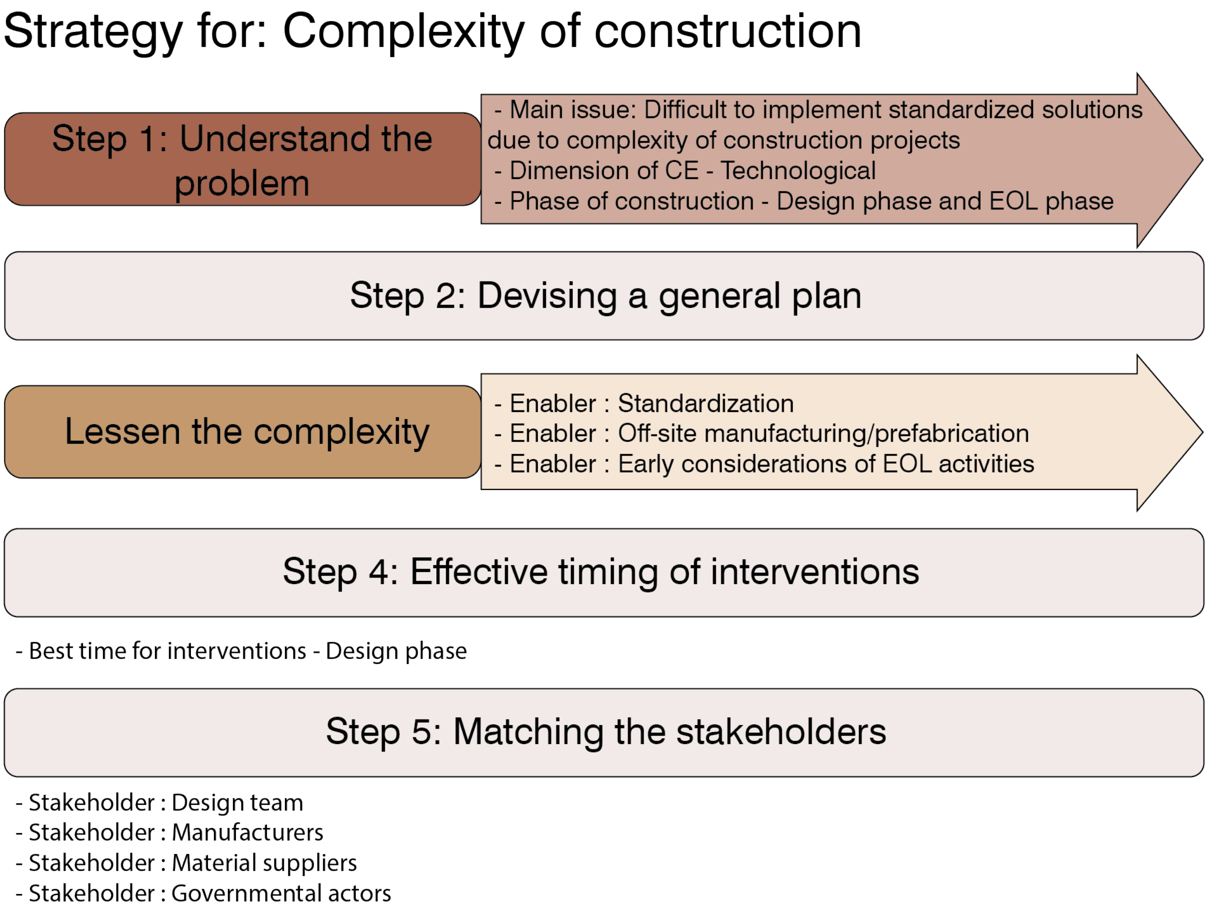


Figure 17. Strategy for the barrier Complexity of construction

Step one – understanding the problem: This is the first barrier categorized as the medium-low relevance issue. It is an inherent characteristic of construction projects that can be seen in their large scale, multi-layered nature, and project specific approaches which makes it difficult to implement standardized solutions. Such complexity makes it difficult to extract high value secondary materials at EOL, makes construction and deconstruction difficult and time consuming, minimizes options for the use of secondary materials as the stakeholders cannot evaluate their suitability, and complicates data management.

At its core this barrier relates to the "Technological" dimension of CE and affects all phases of the construction practice. In general, while looking at the circularity principles, "Design phase" and "EOL phase" are the most influential.

Step two – Devising the general plan: The solution to this barrier requires strategies to lessen the complexity of construction projects through simplifying the processes and components used during construction. This can be done to make the construction process less complicated while increasing opportunities for better maintenance and material recovery at the late stages of construction lifecycle.

Step three – Matching the enablers: Enablers under "Technological" category are best fit to be used while addressing the given barrier with the general plan devised in the previous step. The most promising opportunities are as follows:

Standardization – This enabler promotes the development of industry standards for building components and procedures to create reproducible solutions applicable to various constructions. It touches upon the topics of material selection, dimensioning and shapes of components, and on-site operations. With standardized construction projects CE interventions become easier and more achievable as each project will no longer require unique solutions. Some of the examples of this approach include prefabrication and modular construction.

Off-site manufacturing/prefabrication – This enabler advocates for replicating environments seen in the past industries that has allowed CE procedures to thrive. By diverting manufacturing processes to the off-site locations, projects increase control of processes through monitoring and repeated tasks. Such an environment simplifies making small interventions and allows for overarching solutions. Additionally, prefabricated elements increase the options for at EOL and component reuse by making construction projects less unique.

Early considerations of EOL activities – The research has mentioned on various occasions the impact of strategic interventions during the design stage. The given enabler proposes connection of forward and backwards logistics taking a complete overview of the lifecycle of construction projects and implementing solutions that will have impact much later on to ensure retention of high value of the building components and materials. Examples of such interventions can be seen with DFD strategies discussed in chapter 3.1.

Step four – Timing of the interventions: The barrier shows the biggest impact during the "Design phase" as this is when all the plans are created for the project and "EOL phase" due to the complication for material extraction and remanufacturing. Moreover, the selected enablers relate to a variety of different phases but emphasize the relevance of early stages of construction. The developed strategies should utilize the knowledge about the entire lifecycle of the construction projects, particularly focusing on the EOL activities, but the interventions need to be made during the "Design phase" to maximize their effectiveness.

Step five – Matching the stakeholders: Specialized actors such as "Design team", "Manufacturers", and "Material suppliers" can provide significant amount of insights about the operations of the construction projects and they should be consulted while developing solutions. Additionally, "governmental actors" can greatly aid in the standardization procedures by developing the necessary benchmarks for the industry to strive for and enforcing compliance to the set standards.

Limited demand for circular products

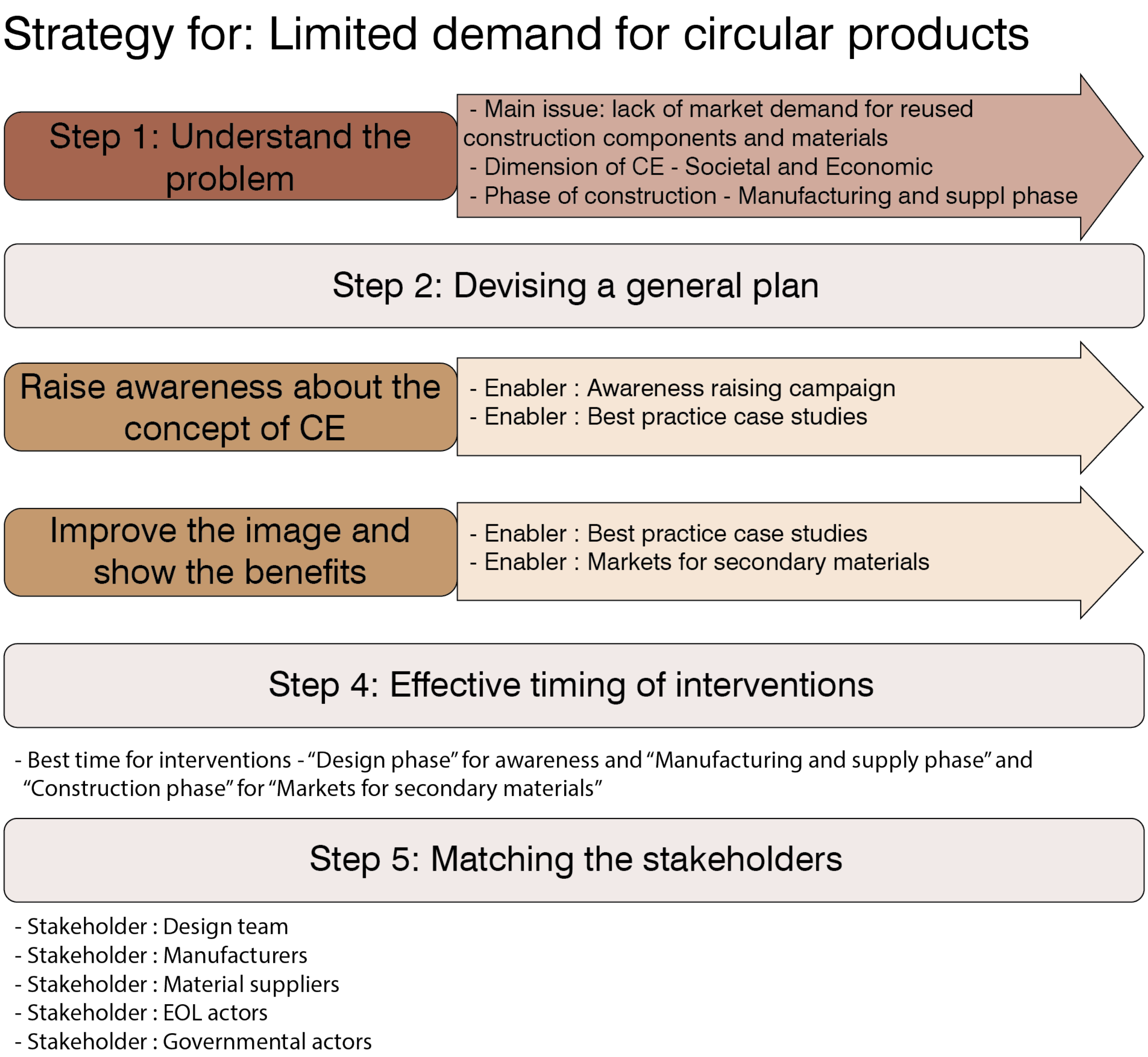


Figure 18. Strategy for the barrier Limited demand for circular products

Step one – understanding the problem: This barrier touches upon the problems related to lack of market demand for construction components and materials that have been reused, recycled, or remanufactured. This discourages manufacturers and suppliers from investing in circular products and services and creates a surplus of reclaimed materials resulting in waste. There are various factors that contribute to the limited demand: 1. Negative perception of reclaimed materials with the public considering them unreliable and unsafe (AlJaber et al., 2023), 2. Lack of awareness with the actors not knowing about the availability or the benefits of circular interventions (Adams et al., 2017), and 3. Lack of a clear business case for using alternative materials (Adams et al., 2017).

The given barrier has strong connections with the "Societal" and "Economic" dimensions and can be seen having the largest impact on "Manufacturing and suppl phase" as the limited demand makes the production of circular products less attractive and limits the validity of its business case.

Step two – Devising the general plan: In order to resolve the barrier of limited demand in an effective manner it is necessary to address all three given issues. The strategies need to raise awareness about the concept of CE, they need to improve the image by showing its benefits and should define the financial viability of the concept by showing successful case studies.

Step three – Matching the enablers: The enablers under the "Societal" and "Economic" categories can be seen to have the greatest potential for addressing this barrier and can be used to achieve the goals of the general plan. The following enablers are best fit for addressing the given barrier:

Awareness raising campaign – The given enabler attempts to resolve the issues stemming from the limited awareness of CE and its benefits from the construction supply chain. It is necessary to educate the future generations by further specifying the benefits of CE during their education process while conferences and events could be used to inform the current practitioners. Better understanding of the topic will affect the demand for circular products.

Best practice case studies – The real-life examples of successfully applied CE principles help in defining a clear business case for the concept by providing demonstratable proof of its financial viability and the safety of using reclaimed materials. While focusing on this enabler, it is beneficial to inform the stakeholders about the long-term benefits and promote taking a lifecycle approach to the scope of construction.

Markets for secondary materials – Looking at more practical solutions, creating refined systems or platforms that facilitate procurement of secondary materials will make it easier for the stakeholders to find, sell, and buy the desirable materials. Such practical solutions make the circular products more desirable and easier to acquire. Additionally, while looking at the reclaimed materials, it is helpful to use digital technologies to manage data through development of digital inventories and BIM to allow for options for information through material tracking.

Step four – Timing of the interventions: While the selected barrier can be seen tied to the "Manufacturing and supply phase", the given solutions should be considered at the earliest possible moments. The solutions focusing on educating the supply chain about the benefits of circular products are relevant at all times, but possession of this information at the "Design phase" greatly increases the opportunities for use of such products and in turn the demand. Meanwhile, enablers like "Markets for secondary materials" give tools that simplify the procurement of reclaimed materials and can be used during the "Manufacturing and supply phase" and the "Construction phase".

Step five – Matching the stakeholders: Various factors contribute to the demand of circular materials thus the strategies require inclusion of many relevant stakeholders. "Governmental actors" are in the best position for increasing awareness about the topics of CE. The "Design team", "Manufacturers" and "Material supplier" should be educated about the benefits of circular materials as they directly contribute to the demand for such products. Finally, "EOL actors" and their operations determine the availability of the secondary resources necessary for production of circular products thus these actors should be educated about and incentivized to operate in a circular manner.

Lack of information/scaled up case studies

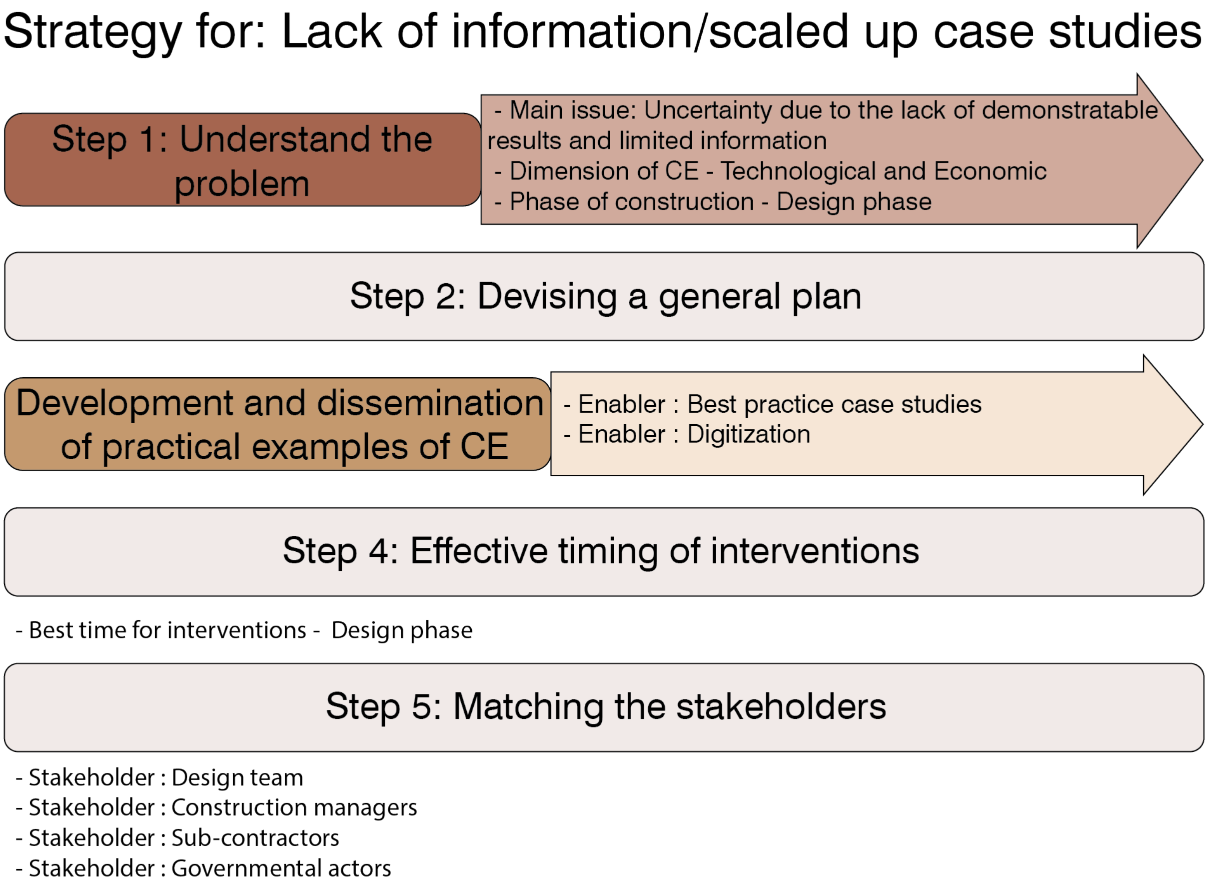


Figure 19. Strategy for the barrier Lack of information/scaled up case studies

Step one – understanding the problem: This was the least relevant barrier out of the 10 presented issues, but it possesses great significance in the context of this research. At its core, this barrier affects the sector through disrupting the information flows, creating uncertainty due to the lack of demonstratable results, and limits the understanding of economic and environmental performance of CE strategies, getting in the way of informed decision making. These issues discourage stakeholders from investing in this new practice and prevent the industry from moving beyond theoretical concepts.

The barrier is categorized under "Technological" and "Economic" dimensions, referring to the lack of available information that demonstrates the economic and general viability of the circular practices. Additionally, the lack of information is a challenge that is apparent throughout the entire lifecycle of the construction projects, but it is particularly impactful during the "Design phase".

Step two – Devising the general plan: To combat this barrier, it is necessary to prioritize development and dissemination of practical examples of CE, by better documentation and information sharing, more accessible information, and funding additional research.

Step three – Matching the enablers: Despite the connections of the barrier to the "Economic" dimension, the enablers under the "Technological" category are perceived to be the best fit for addressing the problems stemming from the lack of information. The most effective identified connections are as follows:

Best practice case studies – The only way to resolve the lack of demonstratable results is by conducting additional case studies and documenting the results. While this might seem like an obvious answer, it is impossible to educate the industry without sufficient information, thus the paper suggests funding additional research, gathering high quality data, and making the findings easily accessible.

Digitization – This enabler provides a more practical solution that allows for additional opportunities for data management. By digitizing the available information about the existing building stock and the future construction projects, it is possible to simplify identification of opportunities and exchanging high value information. This enabler could make use of tools such as BIM and blockchain to create platforms for information monitoring and exchange.

Step four – Timing of the interventions: The solutions for the barrier of lack of information/scaled up case studies don't have specific timing requirements as they are beneficial across the entire lifecycle of construction projects, but information, in general, tends to have more value during the "design phase".

Step five – Matching the stakeholders: The relevant actors for addressing this barrier possess the ability to influence additional research while also have the ability to ensure better monitoring, documentation, and sharing of the available knowledge. "Governmental actors" fit both of these criteria as they can fund additional research and set up platforms for information exchange. Additionally, the actors involved in the production of the circular projects such as "Design team", "Construction managers", and "Sub-contractors" are positioned to monitor and document the circular processes while also being capable of increasing their own understanding of CE to share it with the rest of the supply chain.

With previous chapter, the research has provided the answer to the final sub question SQ5: " *What is the relationship between the barriers, enablers, and the actors of the construction industry and how can these connections be utilized to accelerate the industry wide transition?"*, by categorizing each variable based on their relevance during phase of construction and the dimensions of CE, and matching them with each-other. The given information was used for developing a general approach for dealing with the barriers in the way of adoption of CE which was used to create preliminary strategies for resolving the key hurdles found during the research. This is the final output of the thesis and in combination with the previous findings can be used to give a general answer to the main RQ: *"How can the construction industry accelerate the sector wide transition into a more circular way of operation using the principles of Circular Economy?".*

8. Discussion and limitations

This chapter discusses the findings of the research giving an overview of the interesting results, interpreting the findings and reviewing their implications on the CE in the construction industry. Chapter 8.1 presents the primary results of the report looking at the CE in the construction industry, Barriers, and Enablers. Chapter 8.2 provides the interpretations of the given findings. Finally, chapter 8.3 discusses the limitations of the research.

8.1 Results

8.1.1 CE in construction

The report has highlighted that Circular Economy can serve as a tool meant for addressing the issues of the construction industry particularly in the areas of waste generation, material use, and environmental pollution (Bocken et al., 2016) (Rijkswaterstaat et al. 2022) (Ghisellini et al., 2016) (Mhatre et al., 2021). These challenges are resolved through achieving the primary goal of the CE which aims to minimize waste and pollution through extending the effective lifecycle of construction projects, keeping them in a continuous loop of production (Adams et al., 2017) (AlJaber et al., 2023). This chapter gives a quick overview of important findings about the concept of CE in the construction industry.

Throughout the research, the findings show the relevance of having a concrete definition of the concept to help align the efforts in the same direction and avoid ambiguity surrounding the understanding of this tool (Adams et al., 2017). Taking this into account, the report has developed the following construction industry specific definition of CE: "A construction designed, constructed, used, and reused with the entire lifecycle in mind. It is assembled with optimal materials that are produced in a closed loop system in a manner that allows for easy deconstruction. The construction is an economically responsible, efficient product with an optimal balance between the embodied energy and operational energy use while providing a comfortable environment for its users. It is powered by renewable energy sources and is maintained in an efficient manner to retain the value of the used materials allowing for future reuse of the building components and materials keeping resources in a closed loop." This definition is meant to be used as a starting point for both interventions and future research as a concrete starting point allows for easier understanding and application of the tool.

Looking at the current state of circular operations in the sector, the report has identified 6 categories of strategies that can be currently seen on the market that can be seen in chapter 3.3.2. Among these, the strategies focusing on the designs for disassembly as well as the use of digital tools such as Building Information Modelling were seen to be most prominent, but according to the findings, their application remains still too limited as they are seen more often in one-off projects.

8.1.2 Barriers

The report has utilized two methods for identifying the crucial barriers in the way of CE adoption. The first method utilized the available information from the findings not directly related to the topic to devise the personal list of hurdles, which has led to the identification of 25 problems depicted in appendix B. The second method involved specialized research and analysis of the academic literature which, after removal of duplicates, gave a list of 35 crucial hurdles.

The two methods have resulted in a similar set of findings with the majority of findings being in line with one another. The primary difference was seen in the barriers related to the lack of definition where the personal findings found this to be a major hurdle but was not supported by academic literature. Besides this, it is interesting to see that some of the inherent characteristics of the construction industry such as "complexity of construction" and "fragmented supply chain" were seen as a major barrier in the way of CE adoption.

All the barriers went through a dedicated selection process in order to identify the most critical problems in the way of CE adoption. This process included evaluating the variables based on their number of appearances in academic literature as well as the perceived connections with other barriers. The final list consists of 10 key barriers and can be seen in table 9.

8.1.3 Enablers

Besides the problems, the report has made sure to explore all the available tools in the construction industry that could help in enabling adoption of CE. This exploration was done in a similar manner as in the case of the barriers where first, based on the available information, the report created its own list of enablers followed by conducting a specific systematic literature review.

The self-identified list of enablers contained a total of 35 perceived opportunities that could be used to enhance the circularity of construction practices. Similarly, the systematic literature review revealed a total of 47 enablers after removal of duplicates. The two methods have resulted in an extremely similar set of enablers with only slight differences in wording.

Some of the interesting findings about enablers show that small companies can serve to be market drivers in the supply chain of the construction industry, where they can utilize the niche of circular operations to distinguish themselves from others. This is a unique, yet very relevant enabler that could create additional circular practices that can refine the operations and show the value of CE practice to the entire supply chain. Additionally, the report explored the past successful applications of CE in other industries and has identified 2 key factors that have led to the success of CE in the given sectors. These factors are the "centralized supply chain" and "controlled production environment". Interestingly, the given factors go directly against the inherent nature of the construction industry, and while it is useful to learn from the past, the report has deemed that it is not possible to directly follow in the footsteps of other sectors while seeking for solutions.

The paper recognized the relevance of all the given enablers and decided against further filtering the data under the assumption that the relevance of enablers was reliant on the barriers that need to be resolved and thus it is not logical to eliminate certain opportunities as this could lead to missing specific solutions.

8.2 Interpretation of the results

8.2.1 CE in construction

To begin with it is necessary to address the misunderstandings surrounding the definition of CE in the research. There were two major challenges seen throughout the exploration of the topic that raise the need for clearing up misconceptions.

First, the topic of circular economy can be seen diluted over the years with other schools of thought, most notably the principles of sustainability (Adams et al., 2017). The greatest example of such dilution in academia was observed with the highly regarded works of Pomponi & Moncaster (2017) who put an emphasis on the purely sustainability related factors while discussing CE. These precendents can be seen to have cascading effects on the future research as seen in the reports of Aboutalebi (2023) and Baldew (2023) who were seen evaluating circularity of their research based on sustainability principles. It is important to avoid such delusions as circular economy is still a very new concept especially looking into the construction sector. By its nature, its goal is not endless and has an endpoint after optimizing the existing systems (Geissdoerfer et al., 2017). By continuously adding to the scope of what the tool is meant to accomplish, the core principles are lost resulting in confusion and ineffectiveness of already availably solutions. Such practice only slows down implementation of circular principles, resulting in inconsistent applications, and giving opportunities for surface level solutions and window-dressing (Kanters, 2020).

The second issue directly stems from the first one and it is the problem of inconsistencies in the definition of the concept. It is necessary to align the academic research and practice towards the unified goal with a clear definition to ensure comprehensive approach to systematic transition. This research has given a construction industry specific definition of the concept, and it hopes the given result will be used as a starting point for future research and development.

Looking a bit deeper at the preliminary strategies, it is possible to see that the used variables, particularly in the case of stakeholders, are not used equally. The stakeholders like “Users” and “Resource storage and logistics actors” were not mentioned even once, hinting at their supposed limited importance. While it is tempting to simply shorten the list of variables, such as stakeholders and enablers, to show only the most relevant ones that are used, the research keeps these to provide the widest information base possible. This way future research, focusing on different barriers and enablers, can use the given data to create new strategies.

In a broader sense, it is clear that there is a significant lack of CE specific information in the industry due to the limited applications and large-scale pilot projects. While the report recognizes the value of improved theoretical understanding of CE principles, it is important to note that without real life applications it will not be possible to validate the findings. It is necessary to acquire additional data from the real-world pilot projects and spread this information to increase the validity of the academic research while also giving the supply chain of the construction industry ability to make more informed decisions about the circular operations.

8.2.2 Barriers

There were various interesting findings with regard to the barriers of CE adoption in the construction industry. The first issue that needs to be addressed is the disconnect between the personal findings and the academic literature with regards to the relevance of the unclear definition as a barrier. While the literature does recognize the lack of clarity in the definition to be a general problem (Banihashemi et al., 2024) (Mhatre et al., 2021), there is a lack of research specifically into the topic which was observed by no direct recognition of this barrier during the SLR. There are two potential possibilities for such disconnect.

First, each academic article has slight variations in wording for similar topics. This research was conducted by a single researcher, and it is possible that due to some personal errors or interpretations of specific description, the barriers touching upon the lack of definition were overlooked. The second possibility is more problematic as it could mean that the lack of a clear definition can be seen as an "Unknown unknown" where it is a problem that the academia is not aware of. This issue could have arisen from the reliance on the expertise of the industry practitioners about the topics of CE where the interviewees might not have the same view on the topic. An example of the given case can be observed in the interviews of Van Velzen (2023) where the interviewees were surprised that CE had a wider application than just material reuse: "*So that it's also adaptive and flexible. That's a broader and pleasant definition, better than just material reuse*".

The second interesting observation can be made while looking at specific highly relevant barriers such as "Complexity of construction" and "Fragmented supply chain". These issues are the inherent characteristics of the industry and very difficult to resolve. While dealing with such barriers the research recognizes two options. First, due to the nature of the construction sector, certain solutions are simply not usable and should be overlooked for something more applicable. The second approach views these characteristics as the problem and looks for ways to alter them to address the deeper issues. The latter is clearly a more challenging task, but the main aim of the research is to achieve a systematic transition of the entire construction sector and with this approach the strategic interventions can establish the necessary processes and habits that can make CE principles more applicable. An additional, in-depth, research is necessary for better understanding of the inherent characteristics to find ways to alter them.

Finally, two clear observations can be made while looking at the final list of highly relevant barriers. First, it is clear that the economic barriers are recognized to be the most relevant. This is a logical outcome as money is the primary driver of any industry, but due to the capital-intensive nature of construction projects this seems to be more pronounced in this sector. Due to such strong ties to the economic factors, it is likely that the most influential change will have to be based on a monetary approach. Either the industry needs to adopt a long-term approach to monetary gains and payback periods, or it needs to be nudged through financial incentives with either rewarding circular practices or punishing polluting operations.

Additionally, environmental benefits were clearly not a relevant factor while looking at the barriers where all the important hurdles focused on either economic, technological, or knowledge-based problems. This further illustrates that the current construction industry prioritizes money during the decision-making process and overlooks the less quantifiable benefits such as environmental gains.

Finally, due to the significance of monetary decisions, the strategies for transitioning into circular modes of operation seem to be very limited. The primary way to address and bypass this issue seems to be through policy interventions. This can be deducted due to the perceived relevance of Governance/policy related barriers as well as the significant power of the governmental actors that can loosely dictate the activities of every stakeholder of the supply chain. While significant interventions can be expected to be met with certain level of backlash, governmental interventions through policies and regulations remain the most influential tool for strategic interventions.

8.2.3 Enablers

The research has given a comprehensive overview of the factors that have the potential to enable CE implementation in the construction industry. Moreover, it was recognized that their relevance is reliant on the issues that need to be resolved making it illogical to look for most influential enablers. Due to the nuanced nature of opportunities, it is necessary to look in every possible direction to find opportunities that can be used to resolve emerging problems.

Following the given line of reasoning, the paper looked into the past applications of CE in various sectors to look at the successful examples. Doing so, the research found that the manufacturing and industrial sectors focusing ono the production of simple consumer products could be seen as primary success cases of CE application. Looking deeper into the given industries, the report has determined two primary contributing factors to the success of CE principles in 1. Centralized supply chains and 2. Highly controlled production environments. While combining these findings with the insights into the barriers, the report came to a standstill as the inherent characteristics of the construction industry seem to directly get in the way of the success factors of the past. There are two ways to look at this scenario.

First, due to the inherent differences, it can be assumed that the success factors of the past can not be replicated in the construction industry and instead, solutions need to look elsewhere for more applicable opportunities. This would lead the research to overlook the given enablers limiting the opportunities.

The alternative approach requires gaining a better understanding of both the inherent characteristics of construction and the success factors. This could give information on how the construction industry got to the point where it is right now as well as a deeper knowledge of what contributed to the success of CE in alternative sectors. With a more in-depth approach, strategies can single out solutions that can be used in construction or investigate the options of altering the inherent characteristics to match the other industries. With a deeper understanding, it is possible to make critical decisions and avoid missing opportunities that could enhance CE in construction.

Next, the research needs to consider the value of looking at more industries that utilize CE not only historically but also in the current day. It is necessary to take a comprehensive approach while developing strategies and to that end the construction sector needs to learn form the others and adapt to keep up with the increasing demands from the population growth and urbanization in a circular manner.

Finally, the best practice moving forward would be to try to apply as many enablers as possible. It is clear that there is a lack of understanding of the practical applications of the circular principles. Instead of looking at the ideal theoretical solutions, it is necessary to align academia and practice to lead to the creation of new knowledge through production of circular construction projects. An ideal enabler to utilize for this approach would be allowing smaller companies to act as industry leaders as they can take the risks that the larger actors of the industry would not be willing to take. In the process, such companies can increase their expertise and show the competitiveness of the alternative solutions. It is important to note that the results do not need to be positive for the benefit of the industry as by applying the academic theories in the real practice it is possible to learn what works and what doesn't and how doe these enablers operate in the real-life construction projects.

8.3 Limitations of the research

With this chapter the report acknowledges the limitations that might have affected the validity and the reliability of the findings. It discusses the limitations and drawbacks of the conducted research to ensure transparency and allow the reader to understand the full process of the literature research and synthesis.

First of all, the paper has conducted various systematic literature reviews on the defined database, thus the validity of the findings is heavily reliant on the quality of the used articles. While great care has been taken while selecting and filtering articles, the entire process was conducted through a singular researcher which introduces bias to the gathered papers.

Moreover, the selected literature was only gathered from the Scopus database, potentially excluding highly relevant articles in the other databases. Additionally, looking at the selected literature, the research has filtered lots of information cutting down the original dataset of 600 articles to 59. Due to such a large number of exclusions, it is likely that relevant data was missed. Furthermore, the gathered data, while being very recent, has excluded numerous new articles due to the lack of citations, as they were seen to be unreliable thus it could be missing new breakthroughs.

Looking at the larger picture, the report relies primarily on literature to validate all of its findings and doesn't have any empirical data due to the complications of finding research internships. This is problematic, and somewhat counterproductive, as one of the biggest issues found during the report was the fragmentation of academia and practice. While an attempt has been made to include as many articles that base their findings on empirical research as possible, this does not guarantee the validity of the findings in real-world application. Moreover, the used literature was focused on the articles conducted in the European regions, thus the results cannot be extrapolated to the countries outside the EU. Additionally, the findings have not been tested in the real-world applications, further limiting the validity of the results.

An observation can be made about the general approach of the research focusing heavily on solutions for new constructions, with limited solutions for reuse. While it is true that the report acknowledges the necessity of a lifecycle approach for the issues of CE, the proposed strategies do not directly reflect the need for interventions in the existing building stock. More specifically, the majority of the solutions are looking at EOL phase for potential deconstruction and recycling while not proposing clear options of reuse other than suggestions of flexible design.

Finally, the identifies strategies as well as categorization and many of the other aspects of the report are based on the personal interpretations of the findings from the researcher. The report states where this is the case for transparency reasons, but validity of the final findings is reliant on the correct understanding and interpretations thus, in case of the use of these results for further research, the given data needs to be validated.

9. Conclusion and recommendations

The primary task of this research was addressing the polluting nature of the construction industry by looking into the concept of Circular Economy as a solution. The paper has analyzed various academic articles in an attempt to identify ways on which the construction industry could accelerate its transition into circular mode of operation in order to answer the following question RQ: “How can the construction industry accelerate the sector wide transition into a more circular way of operation using the principles of Circular Economy?”. The research has recognized the complexity of answering such questions and attempted to split the main questing into five smaller sub-questions. This chapter concludes the findings of the report and provides an answer to all the SQs and the main RQ.

The first step to resolving the main RQ was answering SQ1: “What does the Circular Economy entail in the context of the construction industry and how is the concept utilized in modern construction practice?”. While attempting to answer this SQ the paper has conducted the SLR to explore the origins of CE in an attempt to gain a better understanding of the concept, its past applications, and its core ideology. Following this, the research has explored the characteristics of the construction industry and the state of the art of CE in the sector. This has resulted in various findings, mainly it has shown the context of the issue paper aims to resolve, a construction industry specific definition of CE, and various frameworks that were later used for categorizing barriers and enablers.

After answering SQ1, the research has diverted its attention to SQ2: “Who are the stakeholders involved in the construction industry and what power do they hold over adoption of a CE?” exploring literature to identify the most crucial actors of the sector. Originally, the paper identified 28 stakeholders. This list was refined by filtering actors based on their relevance and impact. The final findings gave a list of 12 stakeholders that was later used for developing strategies for CE adoption.

With SQ2 the research finished defining the context of the construction sector and moved to defining the main problem by answering SQ3: “What are the most important barriers that limit the widespread adoption of CE practices in the construction sector that halt the industry wide transition? “. This research has included summarizing the previous findings to look for the barriers in the way of CE adoption and conducting an SLR to view the academic opinion of the issues. In total, the paper found 25 self-identified and 121 reviewed barriers. The previous findings found high correlation with the newly found data which showed the validity of the findings. The large list of barriers was cut down to 10 most influential issues through evaluating them based on their relevance and impact through methods used in other scientific articles.

With the identification of most relevant barriers, the research moved onto looking for available opportunities in the shape of enablers of CE by answering SQ4: "What are the enablers that can enhance the widespread adoption of CE in the construction industry?". This research followed a similar process to the exploration of barriers with the exception of the evaluation process, as it was deemed unnecessary. In total, the analysis has found 35 self-identified and 174 academic enablers with incredibly high correlation between the two. After removing the duplicates and combining the similarly worded enablers, the paper has ended the research with 47 enablers.

After identifying all of the barriers, the paper moved onto resolving the final SQ5: "What is the relationship between the barriers, enablers, and the actors of the construction industry and how can these connections be utilized to accelerate the industry wide transition?". This question required finding matching barriers and enablers and using these correlations alongside the available stakeholders to develop comprehensive strategies for resolving the barriers. The paper categorized each of the variables based on the previously designed frameworks and used the categorized data for identifying interconnections. To answer SQ5 the research has designed 10 barrier specific interventions that gave strategies displaying the most effective pathways to addressing the issues, the timings of interventions, and the important actors and the ways to interact with the said stakeholders to resolve the problems stemming from the barriers.

Finally, the research recognizes the complexity of the task of achieving industry wide transition of the construction industry into circular mode of operations. It admits the need for a comprehensive, collaborative approach from the entire supply chain of the sector to reaching the said goal. Due to this, it has attempted to create the most comprehensive baseline of information that can be used to tackle the problems of RQ. The paper has developed ten specific strategies for intervention that address the largest barriers in accordance with the conducted research. While this does not give a complete answer to the RQ, it can serve as a starting point for the solution. The research has ensured the transparency depicting all the used methodology and presented all of the findings allowing for future researchers to use the paper as a steppingstone for developing a more comprehensive answer.

Recommendations for future research

The given research was conducted under strict time limitations as well as by a singular researcher, thus the paper has set specific boundaries in order to make it possible to complete the thesis within the given time frame. Chapter 8.3 has already given the overview of the primary limitations of the findings. Here, the paper gives general recommendations for future research.

First of all, it is necessary to validate the given findings to ensure the credibility of the results. This should be done by exploring the given dataset and allowing other researchers to draw their own conclusion. Additionally, the results need to be tested in real world applications, specifically the contents of chapter 7.4 as this shows the general approach to problem solving and could be applied to any barrier in practice.

The report has given a comprehensive list of enablers to ensure it doesn't overlook specific opportunities. For future research, it would be recommended to look into each of the identified 47 enablers to gain a deeper understanding of how these tools work and how they can be applied to real construction projects.

Moreover, the thesis has looked into past successful applications of CE and identified two major factors that have led industries such as manufacturing to circular operations. To gain a more comprehensive overview of the opportunities, it is recommended to explore not only past but also the current applications of CE in the other sectors, looking at the successful examples and working with the actors of the given industries to develop strategies applicable to the construction. With this approach it is necessary to look at not only the theoretical solutions used elsewhere but also analyze and apply it to the environment of construction projects.

Finally, the research recommends taking a more aligned approach to ensure comprehensive scanning and analysis of all the available information. This paper has cut down the original dataset of 600 articles to only 59 academic papers. Moreover, many of the used sources could be seen in other articles implying that most of the information used non conflicting data. For the future research, it would be recommended to increase the number of explored articles and instead of cutting on surface less relevant topics, working alongside other researchers to minimize the chances of missed opportunities, giving the most comprehensive results possible. Additionally, the most recent studies should be scanned in a timely manner to include the newest breakthroughs.

10. References

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Appendix

Appendix A

Table 15. A1 Similarities between sustainability and CE based on (Geissdoerfer et al., 2017).

Aspect	CE	Sustainability
Generational commitments	Preserves resources for the future generations and addresses environmental issues.	Fulfills the needs of present generation without compromising the ability of future generations.
Scale	Addresses issues at a global, planetary scale with the focus on resources.	Global approach tackling social, environmental, and economic challenges.
Interdisciplinary approach	Utilizes multi and interdisciplinary approach for achieving economic and non-economic goals.	Integrates social, environmental, and economic disciplines to reach sustainable development.
Value creation	Focus on economic aspects but also utilizes opportunities for environmental value creation.	Balanced view between economic, environmental, and social benefits.
Cooperation	Cooperation is not only desirable but essential for reaching circular goals.	Multi-stakeholder cooperation at various scales required for addressing all 3 pillars of sustainability.
Incentive structure	Stakeholders are incentivized based on regulations and policies.	Ensures compliance based on regulatory and policy frameworks.
Role of private business	Plays central role due to the capabilities and resources to drive circular innovation.	Key players responsible for adopting sustainable practices and driving innovation for long-term impact.

Table 16. A2 Differences between CE and sustainability based on (Geissdoerfer et al., 2017).

Aspect	CE	Sustainability
Goals	Closing resource loops, eliminating waste.	Open-ended goals, balancing 3 pillars of sustainability (priority depends on the user).

Motivation	Optimizing resource consumption and reducing pollution.	Benefiting environment, economy, and society.
Beneficiaries	Economic actors that implement CE and environment, society as a byproduct.	Society, Economy, and Environment.
Priority	Economic system and environment.	Balanced focus between economic, environmental, and social benefits.
Responsibility for implementation	Governments, policymakers, and private businesses.	Shared responsibility for all.
Timeframe	Based on the thresholds set for system optimization.	Open-ended, "maintain the current state indefinitely".

Appendix B

The identified barriers of CE from the chapters 1, 2, and 3 based on the personal findings (Highlights show the connections to the barriers in table 9):

1. Limited adoption in practice
2. Current CE frameworks lack the nuance to capture the inherent complexities of the construction industry
3. Fragmentation of the research on the topic of CE leads to independent findings from the academia and practice
4. Limited understanding of CE in construction
5. Lack of a universally accepted definition
6. The concept of CE is diffused with sustainability
7. Varius strategies, such as "refuse" are not possible due to the high demand from the housing sector
8. Project based approach
9. Uncertainty due to the long lifespan of buildings
10. Use of high EE materials
11. Uncertainty during onsite operations
12. Fragmented supply chain
13. Difficulty of getting high quality information in a timely manner
14. High costs associated with the sector/Scale of projects (each decision is costly)
15. Uncertainties during production (long construction phase (more opportunities for things to go wrong)
16. High upfront transition costs
17. Traditional, risk averse industry
18. Strict regulations for safety (no wiggle room for optimization)
19. Lack of incentives for innovation (no market leaders)

20. No standardization and lack of expertise on secondary materials
21. Inability for mimicking past solution due to the inherent differences of the construction industry
22. Technological limitations for recycling (retaining high value at EOL)
23. Limited wide-scale pilot projects
24. Short-term Rate of Return preference over long-term benefits
25. Limited expertise of the industry

Table 17. B1 The full list of Barriers of circular economy including the sources

Barrier	Source
Complexity of buildings	(Adams et al., 2017) (AlJaber et al., 2023) (Ding et al., 2023) (Shooshtarian et al., 2022) (Eray et al., 2019)
Fragmented supply chain	(Adams et al., 2017) (AlJaber et al., 2023) (Eberhardt et al., 2020) (Zvirgzdins et al., 2019) (Ding et al., 2023) (Minunno et al., 2018)
Low value of materials at EOL	(Adams et al., 2017) (AlJaber et al., 2023) (Owojori & Okoro, 2022)
Unclear financial case	(Adams et al., 2017) (Lee et al., 2023) (AlJaber et al., 2023) (Kanters, 2020) (Pomponi & Moncaster, 2017) (Zvirgzdins et al., 2019) (Ding et al., 2023) (Minunno et al., 2018)
Lack of market mechanisms for material recovery	(Adams et al., 2017) (AlJaber et al., 2023) (Kanters, 2020) (Ding et al., 2023) (Owojori & Okoro, 2022) (Shooshtarian et al., 2022) (Eray et al., 2019)
Limited considerations of EOL issues	(Adams et al., 2017) (Ding et al., 2023)
Lack of incentives	(Adams et al., 2017) (Lee et al., 2023) (AlJaber et al., 2023) (Pomponi & Moncaster, 2017) (Owojori & Okoro, 2022)
Lack of knowledge/Expertise on CE	(Adams et al., 2017) (Lee et al., 2023) (AlJaber et al., 2023) (Kanters, 2020) (Zvirgzdins et al., 2019) (Minunno et al., 2018) (Owojori & Okoro, 2022) (Eray et al., 2019)
Lack of interest	(Adams et al., 2017) (Lee et al., 2023) (AlJaber et al., 2023) (Kanters, 2020) (Minunno et al., 2018) (Owojori & Okoro, 2022) (Shooshtarian et al., 2022)
Low value of the existing building stock	(Adams et al., 2017) (Ding et al., 2023) (Owojori & Okoro, 2022) (Eray et al., 2019)
Unequal distribution of benefits/losses	(Adams et al., 2017) (Kanters, 2020) (Zvirgzdins et al., 2019)
High upfront adoption costs	(Lee et al., 2023) (AlJaber et al., 2023) (Kanters, 2020) (Pomponi & Moncaster, 2017) (Zvirgzdins et al., 2019) (Ding et al., 2023) (Minunno et al., 2018) (Owojori & Okoro, 2022) (Shooshtarian et al., 2022)
Lack of demand for secondary products	(Lee et al., 2023) (AlJaber et al., 2023) (Kanters, 2020) (Ding et al., 2023) (Owojori & Okoro, 2022) (Shooshtarian et al., 2022) (Eray et al., 2019)
Unclear policy support	(Lee et al., 2023) (AlJaber et al., 2023) (Kanters, 2020) (Minunno et al., 2018) (Owojori & Okoro, 2022) (Shooshtarian et al., 2022)
Technology	(Lee et al., 2023) (Kanters, 2020) (Ding et al., 2023) (Owojori & Okoro, 2022)
High time cost at EOL	(Lee et al., 2023) (Kanters, 2020) (Ding et al., 2023) 13
Lack of vision	(AlJaber et al., 2023)
Lack of information/limited case studies	(AlJaber et al., 2023) (Zvirgzdins et al., 2019) (Ding et al., 2023) (Minunno et al., 2018) (Shooshtarian et al., 2022) (Eray et al., 2019)

Limited standardization for secondary materials	(AlJaber et al., 2023) (Ding et al., 2023) (Owojori & Okoro, 2022) (Shooshtarian et al., 2022)
Rigid building codes	(AlJaber et al., 2023) (Kanters, 2020) (Minunno et al., 2018) (Eray et al., 2019)
Difficulty measuring CE	(AlJaber et al., 2023) (Zvirgzdins et al., 2019) (Shooshtarian et al., 2022)
Cost of removing contaminated materials	(AlJaber et al., 2023) (Shooshtarian et al., 2022)
Lack of necessary infrastructure	(AlJaber et al., 2023) (Kanters, 2020) (Shooshtarian et al., 2022)
On site constraints	(AlJaber et al., 2023) (Shooshtarian et al., 2022)
Conservative/Risk averse industry	(AlJaber et al., 2023) (Kanters, 2020) (Zvirgzdins et al., 2019) (Owojori & Okoro, 2022)
Need for simultaneous transition of the entire supply chain	(Kanters, 2020)
Focus of operational phase of construction	(Kanters, 2020)
The risk of eliminating certain professions	(Kanters, 2020)
Communication	(Zvirgzdins et al., 2019) (Minunno et al., 2018) (Shooshtarian et al., 2022)
Emissions during transportation	(Ding et al., 2023)
Lack of scaled up case studies	(Minunno et al., 2018)
Lack of market drivers	(Wielopolski & Bulthuis, 2022)
Bureaucracy during project allocation/tendering	(Wielopolski & Bulthuis, 2022)
The final decisions are made by client	(Shooshtarian et al., 2022)
Cost of alternatives	(AlJaber et al., 2023) (Adams et al., 2017) (Minunno et al., 2018)

Appendix C

Interdependency analysis

Unclear policy support: ambiguity in the policies and legislation creates uncertainties in all parties of the construction industry. This barrier affects all the other barriers in the form of lack of clarity about the topic, lack of incentivization, and lack of sufficient facilities that allows for circular operation such as infrastructure. The interdependencies with other barriers are discussed below.

- High upfront costs: The lack of clarity in the governmental support creates a perception of uncertainty around the topic of CE, making the businesses hesitant to invest in this practice.
- Unclear financial case: The novelty of circular practices and the lack of large case studies limits the available information and creates uncertainty in the industry. By failing to

provide clear policies with regards to the subject governments only increase the perceived uncertainty around the topic, further deterring investors and weakening the business case.

- Lack of knowledge/expertise: Without clear directive from the policies, the industry professionals lack the incentives to educate themselves about circular practices.
- Lack of market mechanisms for material recovery: The construction industry has operated in a linear way depending on virgin materials for a long time and it currently lacks the mechanisms necessary to shift its supply to secondary materials. Without the clear backing from the policies, there is no incentive to establish the necessary infrastructure and practice.
- Lack of interest: Currently the industry shows no interest in exploring circular practices which can be altered by creating supportive policies and financial incentives.
- Limited demand for circular products: Without policy incentives, the industry doesn't see the need to invest in alternative products keeping the demand on circular products low.
- Fragmented supply chain: The complex supply chain of the construction sector is composed of many self-interested actors which makes it difficult to create a coordinated approaching towards resolving CE related issues and without clear incentives from policies it is unlikely to see a change in this approach.
- Limited knowledge/scaled up case studies: The research on any topic is initiated through financial or policy incentives which leads to more case studies.
- Complexity of buildings: Governments regulate construction practice through various regulations steering the path for new ways of operation. Regulations related to the deconstruction and material reuse can lead to new practical solutions simplifying the projects.

Unclear financial case: Novelty of the CE concept in construction and its limited application in the industry creates uncertainties about the financial viability of the concept which deters the actors from implementing circular principles.

- High upfront costs: Committing to the circular practice is an expensive endeavor that requires a large amount of investments. Without a clear financial case it is difficult to attract investors as it is difficult to quantify the benefits of committing to this method of operation.
- Lack of knowledge: The benefits of CE are hard to quantify, this is issues is further increased when dealing with the industry that lacks a sufficient understanding of the concept.
- Lack of market mechanisms for material recovery: Without sufficient systems in place that aid circular operation it is difficult to commit to costly venture of circular operation.
- Lack of interest: Without clear way to quantify the benefits of circular systems it is impossible to raise the interest of the stakeholders.
- Lack of demand for circular materials: The perceived lack of benefits of using circular materials only decreases the demand and requires a clear way of evaluating benefits.
- Fragmented supply chain: The self interested nature of construction stakeholders create an environment where the actors hesitate to commit to new practice without clearly observable benefits.
- Unclear policy support: Without clear financial incentives from the government it is difficult to make a case about the financial viability CE.
- Lack of information/case studies: Without a clear financial case for the relevance of CE there is no incentive for conducting research about the topic.

- Complexity of buildings: The highly complex nature of the construction make it difficult to conduct necessary activities such as deconstruction which adds to the costs.

Fragmented supply chain: The fragmented nature of the construction supply chain is directly intertwined with many of the issues faced by industry. The lack of coordination resulting from this barrier can impede material flows, inflate costs, and limit knowledge transfer.

- High upfront costs: The lack of supply chain coordination complicates the tasks associated with circular operation increasing the costs of activities such as sourcing, processing, and reusing materials.
- Unclear financial case: The fragmentation of the construction industries supply chain creates a diffusion of goals with each actor striving for different goals. It is difficult to find an approach that caters to each actor making it harder to create clear financial cases for circular practices.
- Lack of knowledge: The absence of a unified supply chain makes information sharing difficult, getting in the way of knowledge transfer and expertise about CE practices
- Lack of market mechanisms for material recovery: With the limited incentive for circular operation and the lack of necessary systems in place to simplify the practice, the uncoordinated supply chain of the construction industry is unable to establish effective systems for material take-back, reuse, and recycling
- Lack of demand for circular materials: similar to the previously stated connections, without an incentive to operate in circular manner the self interested actors will not alter their way of operation keeping the demand on circular materials low.
- Unclear policy support: Without any effective communication or collaboration within the industry it is difficult to create effective regulations and incentives due to the limited information.
- Complexity of buildings: The complexity of buildings makes it difficult to conduct circular activities such as deconstruction, with the limited exchange of information, this only becomes more difficult.

Lack of knowledge/Expertise on CE: The lack of understanding about CE affects almost every aspect of its adoption. Some of the challenges include: creating uncertainty, increasing costs, slowing innovation, and affecting stakeholder perception.

- High upfront costs: Without sufficient understanding of the concept from the actors the perception of uncertainty increases, making investors hesitant and increasing the costs.
- Lack of market mechanisms for material recovery: Without sufficient knowledge or expertise it is not possible to develop effective systems for secondary materials.
- Lack of interest: Lack of information limits awareness around the topic of CE which, in turn, lowers interest in the subject.
- Lack of demand for circular materials: without an awareness about the availability of circular products it is impossible to increase the demand.
- Unclear policy support: limited understanding and expertise with regards to CE from policymakers limits their ability to implement effective incentives to lead the industry in the right direction.

- Limited knowledge/scaled up case studies: The limited knowledge of CE impacts the quality of the research and conversely the lack of available research contributes to the lack of knowledge.
- Complexity of buildings: The complexity of the building demands a high level of expertise from the professionals working on them. Without sufficient knowledge of all aspects of construction it is impossible to implement CE in projects.

High upfront adoption costs: This is an economic barrier that determines the economic viability of the concept making it hard to justify investments.

- Unclear financial case: The high upfront costs related to the transition make it an unattractive venture for the investors.
- Lack of knowledge: The lack of expertise on the topic of CE shows the need for additional research and training of the actors, which demands additional funds.
- Lack of market mechanisms for material recovery: Establishing a system for material recovery without any available resource demands high financial investments.
- Lack of interest: The large financial commitment necessary to the transition to the circular practice make it an unattractive endeavor for the stakeholders to engage in without clear quantifiable benefits resulting in the lack of interest.
- Fragmented supply chain: The inefficiencies resulting from the fragmented nature of the industry's supply chain make circular practices less competitive due to higher costs.
- Unclear policy support: Without clear governmental financial incentives and support the direct costs of transition into circular operation only increase.
- Complexity of buildings: The complexity adds to costs, making it harder for businesses to adopt circular methods.

Lack of market mechanisms for material recovery: The absence of effective material recovery systems increases the difficulty of sourcing secondary materials resulting in higher costs and a bad reputation for recycled resources.

- High upfront costs: Establishing systems for procuring secondary materials requires significant financial investment.
- Unclear financial case: The lack of an established market for secondary materials makes it difficult to use recycled resources, affecting the business case of using CE.
- Lack of knowledge: The design and implementation of material recovery mechanisms require understanding of circular practices.
- Lack of interest: The lack of available mechanisms for circular operation reduces the interest of the industry due to the difficulty of implementation.
- Lack of demand for circular materials: The lack of recovery systems may impede the supply of circular materials, reducing the demand for them.
- Unclear policy support: Without policy support, the development of such mechanisms is slow and inefficient.

Lack of interest: Lack of interest, often arising from economic or informational factors, gets in the way of adoption of CE due to alter established practices. This can overshadow the benefits of the concept driving hesitation in the actors.

- High upfront costs: The perception of high costs necessary for making a transition and the uncertainty surrounding the benefits of the concept reduces interest of the actors for committing to this new practice.
- Unclear financial case: Without clear, quantifiable benefits of adopting CE it is difficult to incentivize stakeholders to engage with circular operations.
- Lack of knowledge: The novelty of CE in the construction industry can be seen by the limited understanding of the topic from the actors of construction which results in limited interest.
- Lack of market mechanisms for material recovery: Without established systems that complement circular practices the concept possesses no leverage for catching the actors' interest.
- Lack of demand for circular materials: Without the urgency of the actors of construction to create circular projects, the specialized products and materials see limited use lowering the demand.
- Unclear policy support: Without clear policy support stakeholders may feel that the transition to a CE is not a priority.

Complexity of buildings: The construction projects are assembled with a multitude of highly valuable, composite materials through highly complex practices. This makes it more difficult to apply circular economy principles due to the practical challenges associated to deconstruction, material recovery, and design for reuse as well as increased financial burden.

- High upfront costs: The complexity of building projects makes their production an already expensive endeavor. Commitments to the new way of operation only increases the costs, creating additional economic uncertainties.
- Unclear financial case: Construction industry has always operated in a linear, "take-make-dispose" way to keep up with the increasing complexity of its projects. Committing to the new way of operation requires significant changes from the sectors that are associated with the processes as well as profit schemes which creates additional uncertainty and makes the business case for CE less attractive.
- Lack of knowledge: A lack of knowledge of circular design methods is further exacerbated when dealing with the development of highly complex products.
- Lack of market mechanisms for material recovery: The complex designs of buildings can make it harder to recover materials for reuse and recycling, getting in the way of adopting CE principles.
- Fragmented supply chain: The complex nature of the construction projects necessitates the inclusion of a diverse range of stakeholders with unique expertise in constructing buildings.
- Unclear policy support: Clear policies and standards for material reuse could help reduce complexity.

Lack of demand for circular products: Limited demand prevents the growth of a circular materials market, reducing their economic viability and disincentivizing creation of the said products affecting their availability.

- Unclear financial case: If circular products are perceived as more expensive and unnecessary their demand reduces.

- Lack of knowledge: If stakeholders lack awareness about the quality and the benefits of circular products, demand will remain low.
- Lack of market mechanisms for material recovery: The lack of reliable storage facilities, procurement options and the supply of reclaimed materials can reduce confidence in the sector and therefore reduce demand.
- Lack of interest: With the perceived uncertainty and the lack of interest in circular products the demand for such goods remains low.
- Unclear policy support: Circular construction can be incentivized through incentive schemes and policies raising the demand for circular products.

Limited knowledge/Scaled up case studies: The absence of real-world examples creates uncertainty about implementation and financial viability.

- High upfront costs: Scaled-up case studies could be used as learning opportunities for reducing the required costs for CE transition.
- Unclear financial case: Successful real-world examples of circular projects could decrease the uncertainty surrounding the topic making the financial case for CE clearer.
- Lack of knowledge: Without enough case studies the knowledge gap remains due to the absence of real-world examples of the practice.
- Unclear policy support: Without evidence or use cases, it can be more difficult for policymakers to effectively navigate the construction industry through incentives and regulations.

Appendix D

Self-identified enablers based on the available information up till chapter 3.4 (highlights indicate connections the enablers presented in table 10):

1. Centralized operation and decision making
2. Standardized resources, practice, and materials
3. Highly controlled, monitored environment for production of construction components
4. Repeatable/Reproducible construction activities and processes
5. High degree of communication
6. Learning from the previously successful industries
7. Designing our waste from the systems
8. Approaching people as users and not consumers
9. Use of sustainable energy sources
10. Refinement of CE definition for unifying efforts in the same direction
11. Optimizing construction systems
12. Temporal/Lifecycle approach to construction projects
13. Interventions during the design stage
14. Off-site production/ Prefabrication
15. Collaboration
16. Clear understanding of the limitations and strengths of the industry
17. EOL considerations at the design stage

18. Use of high strength materials to improve longevity of use
19. Use of secondary materials
20. Establishing material banks and material passport systems
21. Modular construction
22. Optimized logistics/Information management
23. Block chain technology
24. Life Cycle Assessment for quantifying CE benefits
25. Flexible design for construction
26. Optimized risk allocation among construction actors
27. Building Information Modeling
28. Just in time delivery of resources
29. Construction/Equipment sharing models
30. Monitoring and maintenance during operation of constructions
31. Policy incentives
32. Educating industry and society
33. Connecting upstream and downstream actors
34. Transitioning into long term financial models
35. Letting smaller companies take charge to refine business case for CE

Table 18. C1 The Enablers of CE in the construction industry

Enabler	Description	Source
Design tools and guidance	A structured framework for stakeholders of the industry that informs them about the ways in which the concepts of CE can be applied to in real life.	(Adams et al., 2017) (AlJaber et al., 2023) (Shooshtarian et al., 2022)
Measurement tools	Practical tools that can be used to quantify the benefits of CE such as Life Cycle Assessment (LCA) or BIM.	(Adams et al., 2017) (Zhang et al., 2022) (Banihashemi et al., 2024) (Barbhuiya & Das, 2023)
Incentive schemes	Schemes aimed at making CE principles more attractive through financial and non-financial benefits.	(Adams et al., 2017) (Lee et al., 2023) (Zhang et al., 2022) (AlJaber et al., 2023) (Ghufran et al., 2022) (Barbhuiya & Das, 2023) (Shooshtarian et al., 2022)
Incentives to use secondary materials	Financial and non-financial benefits aimed at encouraging the use of secondary resources.	(Adams et al., 2017) (Zhang et al., 2022) (AlJaber et al., 2023) (Eberhardt et al., 2020) (Banihashemi et al., 2024) (Barbhuiya & Das, 2023) (Shooshtarian et al., 2022)
Best practice case studies	Increased quantity of high quality research on real-world projects showing the feasibility and benefits of CE strategies.	(Adams et al., 2017) (Lee et al., 2023) (AlJaber et al., 2023) (Wielopolski & Bulthuis, 2022)
Awareness raising campaigns	Organized efforts for educating actors of the construction industry principles, benefits, and practice of CE.	(Adams et al., 2017) (Lee et al., 2023) (Zhang et al., 2022) (AlJaber et al., 2023) (Ghufran et al., 2022) (Shooshtarian et al., 2022)
Technology for material recovery	Advanced tools and systems that facilitate efficient material recovery at EOL such as BIM or RFID.	(Adams et al., 2017) (Zhang et al., 2022) (AlJaber et al., 2023) (Eberhardt et al., 2020) (Zvirgzdins et al., 2019) (Banihashemi et al., 2024) (Ghufran et al., 2022) (Minunno et al., 2018) (Shooshtarian et al., 2022)

High value secondary materials	Increased availability for secondary materials through developments of markets for recovery and promotion.	(Adams et al., 2017) (Zvirgzdins et al., 2019) (Shooshtarian et al., 2022)
Take back schemes	Systems for increasing manufacturer responsibility at the end of products useful life allowing for retaining the value of products.	(Adams et al., 2017)
Clear business case	A clear economic rationale demonstrating the economic viability and benefits of adopting CE practice.	(Adams et al., 2017) (Lee et al., 2023) (AlJaber et al., 2023)
Collaboration	Cooperative approach between the actors of the construction industry with active participations and information exchange aimed at achieving CE goals.	(Adams et al., 2017) (AlJaber et al., 2023) (Eberhardt et al., 2020) (Kanters, 2020) (Pomponi & Moncaster, 2017) (Barbhuiya & Das, 2023) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Systems thinking	Holistic approach to decision making taking into account the interdependencies between variables to optimize systems.	(Adams et al., 2017)
BIM	The use of building information modeling for optimizing workflow through enabling better design, planning and management of constructions.	(Adams et al., 2017) (AlJaber et al., 2023) (Banihashemi et al., 2024) (Minunno et al., 2018)
Policy support and regulations	Frameworks that incentivize and promote circular practices through regulations, standardization, incentive schemes and planning.	(Lee et al., 2023) (AlJaber et al., 2023) (Kanters, 2020) (Banihashemi et al., 2024) (Ghufran et al., 2022) (Barbhuiya & Das, 2023)
Education and research	Driving innovation by making the available information more accessible while extending the knowledge base through research to find new ways of overcoming existing challenges.	(Lee et al., 2023) (AlJaber et al., 2023) (Zvirgzdins et al., 2019) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Material passports/Material databases	Facilitating recycling, reuse, and better management of building materials through material tracing and informed decision making.	(Lee et al., 2023) (Zhang et al., 2022) (AlJaber et al., 2023) (Banihashemi et al., 2024) (Barbhuiya & Das, 2023) (Shooshtarian et al., 2022)
Long lasting building design	Extending the effective lifecycle of constructions and components through innovative practices and material use.	(Zhang et al., 2022) (Eberhardt et al., 2020) (Zvirgzdins et al., 2019) (Ghufran et al., 2022) (Shooshtarian et al., 2022)
Early consideration of EOL activities	Emphasizing the need of planning deconstruction, material recovery, and reuse at the design stage of the construction projects.	(Zhang et al., 2022) (Eberhardt et al., 2020) (Zvirgzdins et al., 2019) (Banihashemi et al., 2024) (Ding et al., 2023) (Minunno et al., 2018) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Selective demolition	Controlled process of deconstruction that allows the retention of highest value for materials and reduces waste.	(Zhang et al., 2022)

Standardization	Creating a set of uniform practices, reproducible practices that facilitate the reuse, recovery, and recycling of materials and components while simplifying the construction process.	(Zhang et al., 2022) (AlJaber et al., 2023) (Eberhardt et al., 2020) (Banihashemi et al., 2024) (Barbhuiya & Das, 2023) (Minunno et al., 2018) (Shooshtarian et al., 2022)
Setting goals	Creating a clear set of goals and measurable targets for the stakeholders giving a unified direction to strive for.	(Zhang et al., 2022)
Restrictions on landfilling	Policy approach discouraging disposal of CDW and encouraging more circular methods such as material recovery and recycling.	(Zhang et al., 2022)
Sufficient infrastructure	Developing sufficient facilities, systems, and networks that simplify the use of circular practices.	(AlJaber et al., 2023) (Eberhardt et al., 2020) (Minunno et al., 2018)
Material selection/Substitution	The use of appropriate materials for each project with the aim of optimizing material flows and reducing unnecessary emissions.	(Eberhardt et al., 2020) (Zvirgzdins et al., 2019) (Shooshtarian et al., 2022)
Adaptable / Flexible building design	Creating constructions and building components that can be modified, reused, or repurposed over time, reducing waste and extending the effective lifecycle of resources.	(Eberhardt et al., 2020)
Lifecycle approach to scoping	Increased consideration of the full lifecycle of constructions to ensure the decisions made at each stage don't have trickledown effects on other stages.	(Eberhardt et al., 2020) (Zvirgzdins et al., 2019) (Wielopolski & Bulthuis, 2022)
Sufficient building team selection	Choosing the right actors for the projects that have sufficient skills, knowledge, and commitments to operating in circular manner to facilitate collaboration and drive innovation.	(Eberhardt et al., 2020)
Modular design	Unique construction practice that increases the options for adaptable design, efficient disassembly, and use of resources.	(Eberhardt et al., 2020) (Banihashemi et al., 2024) (Minunno et al., 2018)
Offsite construction / Prefabrication	An alternative method for manufacturing that Is conducted in controlled environments allowing for more effective use of resources, waste reduction, and options at EOL.	(Eberhardt et al., 2020) (Minunno et al., 2018) (Shooshtarian et al., 2022)
Component reuse	Extending the effective lifecycle of the building components by keeping it in a closed loop and reusing it in alternative construction projects.	(Eberhardt et al., 2020) (Zvirgzdins et al., 2019)

Optimized shapes and dimensions	Technical enabler focusing on standardizing geometry of construction components to simplify projects and increase options for EOL activities.	(Eberhardt et al., 2020)
Layer independence in buildings	A new way of visualizing constructions by separating materials based on their effective lifespans in layers., allowing for easier maintenance, material recovery, and adaptability.	(Eberhardt et al., 2020)
Sharing schemes	Collaborative use of resources, materials, and equipment among multiple users, aiming to optimize their use and reduce waste.	(Eberhardt et al., 2020) (Zvirgzdins et al., 2019)
Communication	A basic strategy that is key for effective collaboration, information exchange, and stakeholder engagement.	(Kanters, 2020) (Pomponi & Moncaster, 2017) (Barbhuiya & Das, 2023) (Wielopolski & Bulthuis, 2022) (Shooshtarian et al., 2022)
Ownership models	Rethinking the traditional ownership structures and adoption systems such as Product As a Service which shifts the focus from selling to providing a service to encourage manufacture for more durable and easier serviceable products.	(Pomponi & Moncaster, 2017) (Ding et al., 2023)
Procurement strategies / Tendering agreements	Inclusion of CE principles during the tendering phase allow development and selection of the most appropriate construction teams and designs.	(Pomponi & Moncaster, 2017) (Shooshtarian et al., 2022)
Transparency	Open access and sharing of relevant information with regards to construction practice and materials to foster trust, allow for informed decision making, and promote accountability among stakeholders.	(Pomponi & Moncaster, 2017)
Specialized maintenance activities	Proactive strategies for care of construction projects aimed at optimizing performance, extending life, and facilitating reuse or recycling of high value components and materials at EOL.	(Zvirgzdins et al., 2019)
Sustainable energy sources	The use of alternative sources of energy that are less reliant on fossil fuels.	(Zvirgzdins et al., 2019)
Digitalization	Use of modern tools to digitize the existing and the future building stock to provide a clear overview of the existing world and allow for informed decision making with regards to building processes and waste reduction.	(Banihashemi et al., 2024)

Material tracking	Use of technological systems such as RFID chips to monitor, record, and track the status of construction materials and components throughout their lifecycle allowing for easier maintenance and resource management.	(Banihashemi et al., 2024) (Elghaish et al., 2023) (Minunno et al., 2018) (Shooshtarian et al., 2022)
Block chain technology	A powerful tool that provides a secure, transparent platform for managing relevant information that can be used optimize logistics activities, improve trust, and facilitate collaboration.	(Elghaish et al., 2023)
Optimized logistics	Efficient management of material flows covering both forward and backward logistics to improve material tracking and utilizing available tools and technologies to close loops.	(Elghaish et al., 2023) (Ding et al., 2023) (Shooshtarian et al., 2022)
Creating environment for innovation	Establishing collaborative relationships between multidisciplinary actors aimed at fostering development and creating of novice solutions. The better building initiative can be seen as an example framework for this.	(Wielopolski & Bulthuis, 2022)
Waste management strategies	Practices aimed at minimizing waste generation, optimizing the use of resources, and ensuring proper handling of byproducts of construction.	(Shooshtarian et al., 2022)
Extended manufacturer responsibility	Shifting the task of waste management from society to the manufacturers with the aim for incentivizing development of more durable, reusable, recyclable, and less harmful products that retain high value of materials and stay withing the circular systems longer.	(Shooshtarian et al., 2022)
Markets for secondary materials	Creating platforms and mechanisms for recovering, storing, trading, and reusing materials that have already been used in construction projects. These systems are aimed at reducing the reliance on virgin materials and reducing waste by providing attractive alternative options to the industry.	(Shooshtarian et al., 2022)