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# **Exploration of prefabricated concrete construction with a focus on environmental sustainability and circular economy principles.**

Master's thesis in the master's program Design and construction project management

Rasaq Adegboyega  
Serag Al khayyat

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Department of Architecture and Civil Engineering  
CHALMERS UNIVERSITY OF TECHNOLOGY  
Master's thesis ACEX30  
Gothenburg, Sweden 2024



MASTER'S THESIS ACEX30

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Serag Al khayyat

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Supervisor: Dr. Dimosthenis Kifokeris, Department of Architecture and Civil Engineering

Examiner: Dr. Dimosthenis Kifokeris, Department of Architecture and Civil Engineering

Department of Architecture and Civil Engineering

Division Of Construction Management

Chalmers University of Technology

SE-412 96 Gothenburg

Telephone +46 31 772 1000

Department of Architecture and Civil Engineering  
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Rasaq Adegboyega

SeragAl khayyat

Department of Architecture and Civil Engineering

Chalmers University of Technology

## **Abstract**

The construction industry is a major consumer of natural resources, prompting researchers to explore circularity principles for building construction. This study examines the differences between on-site assembly and disassembly practices of prefabricated concrete construction and circular economy principles. The aim is to identify strategies that can increase on-site assembly efficiency while maintaining environmental sustainability. The study also evaluates the opportunities and challenges associated with incorporating circular economy principles to reduce greenhouse gas emissions. Following a comprehensive literature review combined with the analysis of the empirical data from interviews, the study gains insights from industry professionals. The findings suggest that current on-site assembly techniques do not adhere to circularity principles, and the absence of technological integration like BIM, RFID etc., during on-site assembly impedes efficiency and data collection for potential disassembly and reuse phases. It is worth noting that a substantial portion of construction time, 70%, is dedicated to lifting components, which often requires heavy-duty equipment mostly powered by fossil fuels, significantly contributing to carbon emissions.

The study emphasizes the benefits of adopting circular economy principles in prefabricated concrete construction, including increased building value, decreased material use resulting in environmental benefits, and the potential for new business opportunities. However, the study recognizes challenges such as substantial initial investments, standardizing component designs, integrating technology, and establishing storage facilities for reused components. The study suggests optimizing on-site processes to reduce assembly times and labor costs, enhancing competitiveness. This research contributes to the growing body of literature on the circular economy in the construction industry by comparing current practices to circular economy principles and emphasizing the critical role of the assembly phase in component reuse.

**Keywords:** Prefabricated concrete, sustainability, circular economy, concrete components, component reuse, on-site assembly, disassembly.



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# 1

## Introduction

The construction industry is at a crossroads, facing the dual challenge of meeting the growing demand for infrastructure while also addressing environmental concerns. Prefabricated concrete construction (PCC) has emerged as a promising solution, offering potential benefits in terms of efficiency, waste reduction, and sustainability (Mydin et al., 2014; Tam et al. 2007).

This literature review explores the integration of PCC within the frameworks of sustainability and circular economy (CE) principles, examining its potential to reduce greenhouse gas emissions in the construction sector. The exploration of prefabricated concrete construction, with a focus on environmental sustainability and circular economy principles, represents a forward-thinking approach in the construction industry aimed at further mitigating its environmental impact. This approach seeks to harness the efficiency and durability of prefabricated concrete while aligning construction practices with the principles of sustainability and circularity.

Prefabricated concrete construction involves the off-site manufacturing of concrete elements, which are then transported and assembled on-site (Guo et al., 2019). This method offers several environmental advantages over traditional construction techniques, including reduced waste, lower energy consumption, and minimizing disturbance to the construction site (Chen & Huang, 2020). By streamlining the construction process, prefabrication can also contribute to a decrease in carbon emissions associated with material transportation and on-site activities (Ji et al., 2020).

The integration of circular economy principles into prefabricated concrete construction is a key aspect of this exploration. Circular economy principles emphasize the reduction of waste, the extension of product life cycles, and the recycling or repurposing of materials at the end of their use (Eberhardt et al 2019). In the context of prefabricated concrete buildings, this could involve designing for disassembly, enabling the reuse of concrete elements in future projects, and developing recycling technologies for concrete materials (Guifen et al., 2019). Such practices not only reduce the demand for virgin materials but also lower the environmental footprint of the construction process (Jiao & Li, 2018).

To explore prefabricated concrete construction in the context of environmental sustainability and circular economy principles, this study considers the differences in on-site assembly and disassembly practices from circular economy principles and their impact on reducing greenhouse gas emissions. Research by Geissdoerfer et

## 1. Introduction

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al. (2017) highlights the significance of the circular economy as a sustainability paradigm, providing a foundation for understanding how prefabricated concrete construction can align with circular principles to reduce environmental impact.

Efficiency in on-site assembly and disassembly practices can be enhanced by strategies that integrate environmental sustainability and circular economy principles. Bonoli et al. (2021) emphasize the role of eco-design, life cycle assessment, and effective waste recycling processes, particularly concrete recycling, in promoting a circular economy in construction. Additionally, research by Eberhardt et al. (2020) demonstrates a substantial reduction in embodied greenhouse gas emissions through the use of prefabricated concrete structures, indicating the potential for efficiency gains in construction practices. An efficient method for constructing prefabricated walls using virtual simulation and Building Information Modeling (BIM) technology has been successfully developed. This approach offers several advantages over traditional on-site construction techniques, including improved manufacturability and on-site assembly. To ensure quality assurance and a smooth assembly process, a comprehensive step-by-step plan was devised and implemented, following the recommendations of Liew & Chua (2021), which utilized a LOD 300 model.

Integrating circular economy principles into the on-site assembly and disassembly of prefabricated concrete components to mitigate greenhouse gas emissions presents both opportunities and challenges. The study by Lausset et al. (2023) emphasizes the importance of design for disassembly (DfD) in achieving climate targets and implementing circular economy principles, aligning with the goals of the European Green Deal.

The research questions posed focus on the differences between on-site assembly and disassembly practices of prefabricated concrete buildings concerning circular economy principles, strategies to improve on-site assembly efficiency while considering environmental sustainability and circular economy principles, and the opportunities and challenges of integrating circular economy principles into the assembly and disassembly of prefabricated concrete components to reduce greenhouse gas emissions.

The exploration of prefabricated concrete buildings and construction, with an emphasis on environmental sustainability and circular economy principles, offers a promising avenue for reducing the construction industry's environmental impact. Through the adoption of efficient construction methods, the integration of circular economy practices, and the utilization of sustainable materials and technologies, this approach aims to foster a more sustainable and resilient future for the construction sector.

# 2

## Literature Review

The construction industry is a significant contributor to the global economy, accounting for 13.5% of the world's GDP and employing 7% of the global workforce. As one of the largest economic ecosystems, this industry has a crucial role to play in achieving global sustainability objectives (Blanco et al, 2021). Although it is not typically considered a pioneer in sustainable practices, there is a growing concern within the entire construction ecosystem to adopt and embrace sustainable methods (Volpe et al., 2021). This literature review examines the intersection of prefabricated construction methods, sustainability, and the potential for circular economy principles to promote sustainable practices within the construction industry.

### 2.1 Prefabricated Concrete Construction

Prefabricated concrete construction involves the manufacturing of concrete components off-site in a factory or at the construction site, which are then assembled to form a structure with minimal in situ construction (Ji et al., 2018). In this part, we delve into the historical development of prefabricated concrete construction, examining its production processes and techniques, as well as its impact on sustainability.

#### 2.1.1 History and Evolution

The historical development of prefabricated concrete construction has seen significant advancements over the years. Research has shown that the concept of prefabrication in housing construction dates back to the 19th century (Yao et al., 2020). Initially, countries like the United States, the United Kingdom, Hong Kong, Sweden, and Australia played a crucial role in pioneering prefabrication technology (Li et al., 2014). However, more recent studies have highlighted the increasing interest and contributions from developing countries like China, and Turkey in promoting research related to prefabrication (Li et al., 2014).

The development of prefabricated buildings has become a global trend, with countries like China adopting prefabricated construction as a key national strategy towards a "carbon-free future" (Cui et al., 2022). This shift towards prefabrication has been driven by various factors, including advancements in concrete mixtures, leading to improved quality and properties of prefabricated concrete (Ahmed & Grănescu, 2019). The construction industry has witnessed a transition towards industrial architecture, with more buildings now utilizing prefabricated concrete over traditional

cast-in-place concrete (Jiao & Li, 2018).

The use of prefabricated structures offers advantages such as increased construction productivity, improved quality, reduced labor requirements, and decreased energy consumption and carbon emissions compared to traditional building methods (Sui et al., 2020). The adoption of prefabricated buildings has led to changes in construction modes, emphasizing sustainability and low carbon emissions (Chen et al., 2022). In fact, these have necessitated advancements in various aspects, including the optimization of structural, hygrothermal, energy, acoustic, fire, and environmental performance (Tsikaloudaki et al., 2022).

The cost-effectiveness of prefabricated residential buildings has also been highlighted, showcasing lower costs compared to traditional concrete buildings (Zhu & Zhang, 2018). However, the research community has emphasized the importance of cost control in the design stage of prefabricated concrete buildings to promote their development (Su et al., 2023). Studies have also highlighted the need for detailed coordination at all project stages due to the complexity of prefabricated construction techniques and the involvement of multiple stakeholders (Ji et al., 2018).

The historical development of prefabricated concrete construction has been marked by technological advancements, increased adoption as a national strategy, and a shift towards more sustainable and efficient building practices (Jiao & Li, 2018). Prefabricated construction methods continue to shape the construction industry, offering solutions that enhance productivity, quality, and environmental sustainability.

### 2.1.2 Construction Techniques and Processes

Construction techniques may be divided into three groups: conventional or customary construction, industrialized or prefabricated construction, and hybrid systems (Mydin et al., 2014). Industrialized construction, the first stage of industrialization in the construction industry, entails manufacturing building components in a controlled factory setting before transporting them to the construction site for assembly using specific connections (Martins et al., 2023).

Industrialized construction techniques in concrete construction have been a subject of significant research and development. This method of construction has seen advancements in various aspects, including construction management, environmental impact assessment, economic benefits, and structural performance (Kim et al., 2015). Prefabrication techniques have also been associated with improvements in structural performance. For instance, the development of novel hybrid prefabricated concrete connections has been explored to enhance the seismic performance of prefabricated concrete frames (Chen et al., 2022). Additionally, advancements in prefabricated shear wall structures have been noted for their convenience in construction, low environmental impact, and high joint quality (Li et al., 2019).

### 2.1.2.1 Design to Installation

The prefabrication process involves several key stages, including design, component production, transportation, storage, hoisting, and installation. Design plays a crucial role in prefabricated concrete construction, with a focus on optimizing frame structures and addressing horizontal-torsional coupling for enhanced performance (Li et al. 2022). The design phase considers sustainability aspects, such as energy efficiency and environmental protection, to align with the principles of sustainable development (Xie et al., 2021). Building Information Modeling (BIM) technology is utilized to systematize the design process and enhance construction efficiency (Kirschke & Sietko, 2021).

Following design, component production involves fabricating prefabricated elements in manufacturing facilities. The production process aims to ensure high-quality components that meet design specifications (Zhu & Zhang, 2018). The use of innovative reinforcement technologies, such as steel half-grouted sleeve connections, enhances the mechanical properties of prefabricated structures (Chen et al, 2022).

Transportation and storage of precast concrete components are critical steps in the process. Real-time optimization techniques are employed to streamline transportation logistics and ensure efficient storage practices. The handling of prefabricated elements during transportation and storage is essential to prevent damage and ensure the integrity of the components (Chuai et al., 2020).

Hoisting and installation are key activities in prefabricated concrete construction. The installation process involves assembling prefabricated elements on-site to create the desired structure. The use of advanced connection techniques, such as wet and dry connections, enhances the seismic performance of prefabricated concrete frames (Chen et al., 2022). Proper joint design and construction are crucial to ensure the structural integrity of prefabricated buildings (Li et al., 2019).

The process of prefabricated concrete construction involves a series of interconnected stages, from design to installation. Each stage requires careful planning, coordination, and adherence to quality standards to ensure the successful completion of prefabricated building projects.

### 2.1.3 Prefabricated Concrete Construction and Environmental Sustainability

Sustainability in the construction industry is a crucial concept that has garnered increasing attention due to its significant impact on the environment, society, and the economy (Liu & Gambatese, 2020). The construction industry plays a vital role in sustainable development, as it provides benefits to society while also causing negative impacts, making it a key sector in the fight for sustainable development (Opoku et al., 2015). Sustainable construction involves various drivers such as legislation, customer requirements, competitive advantage, environmental concerns, and the long-term survival of businesses (Ogunbiyi et al., 2014). These drivers under-

## 2. Literature Review

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score the importance of integrating sustainable practices into construction processes to achieve environmental, social, and economic goals (Jiang & Qi, 2022). The shift towards sustainability is crucial, as the construction industry's activities have significant environmental impacts that need to be mitigated through sustainable practices.

Prefabricated concrete construction has emerged as a significant innovation in the construction industry, offering a promising pathway towards enhancing environmental sustainability (Ji et al., 2020). There are numerous technical solutions available for constructing prefabricated residential and industrial buildings, primarily composed of concrete due to its numerous advantages over other structural materials. A study conducted by Liu et al. (2021) examined critical technical nodes in prefabricated concrete construction, emphasizing the significance of factors such as connection details, assembly processes, and quality control measures in achieving the successful implementation of prefabricated buildings. This underscores the diverse technical solutions required for the efficient construction of prefabricated structures. Concrete possesses high compression strength, exceptional durability, fire resistance, and enhanced thermal insulation through the use of lightweight concrete (Martins et al., 2023).

Several studies have highlighted the advantages of prefabricated construction in terms of sustainability. For instance, Li et al. (2014) emphasized that prefabricated construction is increasingly being adopted worldwide to mitigate the adverse environmental effects associated with conventional construction activities. Xie et al. (2020) further supported this notion by stating that prefabricated buildings have become crucial for achieving sustainable development in the construction process because of advantages such as high construction speed, energy-saving, and environmental protection.

Prefabricated building processes lead to increased efficiency, reduced environmental pollution, and enhanced sustainability in production, construction, and use processes compared to traditional construction methods (Cui et al., 2022; Wu et al., 2022). Wu et al. (2022) stressed the importance of synthesizing environmental, economic, and social sustainability dimensions in promoting prefabrication implementation in the construction industry.

Studies such as the one by Jiao & Li (2018), confirm the advantages of prefabricated concrete in boosting construction efficiency, lowering environmental pollution, and conserving energy. Cui et al. (2022) delve into the benefits of prefabricated buildings, highlighting their efficiency, cost-effectiveness, and energy-saving potential, as well as their reduced environmental impact and overall sustainability during production, construction, and use. Furthermore, Volpe et al. (2021) propose that the integration of prefabricated systems, construction automation, and innovative materials could significantly improve the future sustainability of the construction industry.

In terms of environmental impact, Wang et al. (2022) conducted a study comparing

the greenhouse gas emissions of prefabricated and traditional construction methods, showing that prefabricated methods can reduce emissions per cubic meter of concrete by 10%. Similarly, Thamboo et al. (2021) discussed the potential of prefabricated masonry systems in Australia in terms of structural characteristics and sustainability perspectives, indicating a positive outlook for sustainability. Additionally, sustainability aspects of prefabricated construction are addressed by (Dong et al., 2023), who analyze the links between Design for Manufacture and Assembly (DFMA) and the construction industry. This research highlights the importance of sustainable practices in prefabricated construction, emphasizing the role of efficient design and manufacturing processes in enhancing sustainability.

Although there are numerous benefits associated with the use of prefabricated concrete components, the production of these components can lead to harmful environmental releases, such as dust, noise, volatile organic compounds (VOCs), and radioactive elements (Cui et al., 2022). Studies show that prefabricated footing systems can consume up to 21% more energy and up to 18% more greenhouse gas emissions than traditional construction methods (Teodosio et al., 2021). Moreover, an increase in the prefabricated rate has been linked to a rise in terrestrial ecotoxicity, indicating potential environmental trade-offs (Wang & Sinha, 2021). Transporting these heavy concrete panels to the construction site adds to the carbon footprint of the project (Guo et al., 2019). Nonetheless, Rocha et. al (2022), maintain that prefabricated concrete in the construction industry still has the potential to minimize environmental consequences through optimal production procedures, transportation and installation techniques, and adherence to sustainable resource management principles in line with the circular economy.

Overall, Prefabricated concrete presents a promising solution for reducing environmental impacts in the construction industry by reducing waste, energy consumption, environmental pollution, and offering a more sustainable alternative to traditional construction practices. However, the extensive use of prefabricated construction techniques has led to several environmental issues, in connection with the manufacturing, transportation, and installation of prefabricated concrete components. Hence to maximize its potential, optimal production methods, efficient transportation strategies, and sustainable resource management practices aligned with the circular economy principles should be employed.

## **2.2 Circular Economy Principles in Construction**

Circular economy is a concept that has multiple dimensions and is applicable to various sectors. This section explores the principles and implementation of circular economy in the construction industry, with a particular focus on the construction and assembly of prefabricated concrete components.

### 2.2.1 Fundamentals and Implementation

Circular economy principles, which prioritize sustainability, efficiency, and waste reduction, mark an important change in how we handle resource management, according to Ömer Çimen (2021), “The main pillars of circular economy are further broken down into 10 R principles of Recover, Recycle, Repurpose, Remanufacture, Refurbish, Repair, Re-use, Reduce, Rethink and Refuse”. Adopting these concepts is essential for tackling environmental, economic, and social issues in the construction sector, where resource consumption and waste production are notable (Guerra et al., 2021). Fundamentally, the goals of the circular economy principles are to establish approaches that maximize resource utilization, reduce waste and emissions, and allow natural systems to redevelop. This includes giving up the take-make-dispose linear model and concentrating on extending the useful life of products and materials, promoting the value earned from them while in use, and obtaining and reusing them at the end of their lifespan (Guerra et al., 2021).

Circular economy principles in construction have several important purposes, such as waste reduction, expanded product lifetime, material monitoring, and resource efficiency. These purposes can help the building sector save money, innovate, improve the durability and sustainability of construction sites, and decrease its negative environmental effects (Marsh et al., 2022).

It is especially important to design for disassembly because it makes it easier to reuse materials and components, extending their useful lives and lowering the necessity for any additional resources. Encouragement of material recycling and reuse reduces waste production and utilization of resources even more. Applying a life cycle approach guarantees that at every stage of a building’s existence, from design to destruction, the effects on the environment are taken into account (Hossain et al., 2020).

In order to achieve environmentally friendly building procedures, industry stakeholders must collaborate and be innovative. The construction industry can lessen its impact on the environment, save resources, and help create an improved built environment for both today and the future through the implementation of the principles of the circular economy (Eberhardt et al., 2020b).

In construction, switching from linear to circular models is important for a number of causes. First off, minimizing waste production and increasing the materials’ lifespans, contribute to the preservation of resources. By permitting resource efficiency and reducing the negative environmental effects of construction, this model supports environmental sustainability (Nasir et al., 2017; Rahla et al., 2021). Furthermore, adopting circular models enhances resource usage, lowers expenses for disposal, and eliminates the requirement for new materials, all of which result in major financial savings over time. Furthermore, by employing techniques like material recovery, recycling, and reuse, these models contribute to waste reduction and lower pollution to the environment (Guerra et al., 2021).

By implementing circular models, building techniques will also be in compliance with regulations and will be able to satisfy the growing need for environmentally friendly and sustainable buildings. According to Marsh et al. (2022), this change not only supports sustainable development but it additionally helps to create a built environment that is more adaptable and resource-efficient.

### 2.2.2 Circular Design Strategies

As mentioned, to advance sustainability, resource efficiency, and waste reduction in the building sector, circular design strategies are essential in the construction industry. By highlighting methods that reduce environmental effects and optimize the utilization of resources, these tactics seek to promote a more circular economy in the building sector (Minunno et al., 2018). Architects, engineers, and other stakeholders can help create a built environment that is less harmful to the environment and sustainable by implementing different circular design strategies (Eberhardt et al., 2020b). Here, we examine several circular design approaches that are relevant to the building industry and the benefits that come with them.

One important strategy is to purposefully design buildings to be easily disassembled, allowing for the reuse and recycling of elements and materials at the end of their useful lives. This is known as "design for disassembly." This strategy reduces waste production and maximizes the reuse of resources by permitting the separation of building components (Minunno et al., 2018).

Another crucial strategy is Material Reuse and Recycling, which entails planning for material reuse and integrating recycled materials into building projects (Eberhardt et al., 2020b). Increasing the lifespan of building elements and components is the focus of the Reuse of Replacement Parts and Components initiative (Minunno et al., 2018). therefore lowering the need for constant supplies and support in the reduction of waste production (Eberhardt et al., 2020b).

A method called modular construction refers to manufacturing building components off-site and assembling them on-site. In addition to lowering construction waste, this method facilitates simpler disassembly and restructuring, motivating flexibility and versatility in building design (Eberhardt et al., 2020b).

Reusing existing structures or their parts for future construction projects is known as "adaptive reuse," which greatly reduces the negative environmental effects of construction (Eberhardt et al., 2020b). In order to accommodate simple adjustments and adapt to suit changing demands, buildings and componentry must be designed with adaptability in mind (Minunno et al., 2018). Alternatively, using already-existing structures or their parts in new construction projects, greatly minimizes the impact of the building process on the environment (Eberhardt et al., 2020b). According to Minunno et al. (2018), this also increases the endurance and adaptability of structures, lowering the need for major repairs or rebuilds.

During the construction procedure, putting Lean Production Chain principles into practice improves resource utilization, lowers waste production, and improves efficiency. The research conducted by Son and Tien (2024) utilized lean modeling techniques to simulate finishing work in construction processes, which led to a 13% decrease in construction cycle time, a 141% increase in process efficiency, a 268% improvement in average productivity, and a 96% reduction in labor cost. These findings highlight the potential for Lean principles to yield substantial enhancements in efficiency and cost-effectiveness within construction projects. This approach facilitates cost-effectiveness and sustainability by optimizing processes and reducing ineffectiveness (Minunno et al., 2018).

In order to cut waste and improve resource efficiency, circular material selection entails selecting materials with an emphasis on circularity, such as simple to recycle or low-impact materials. Using such construction components promotes a closed-loop system and lowers the need for new resources. A more sustainable and circular approach to construction is achieved by giving priority to recyclability (Minunno et al., 2018). By monitoring the properties and locations of the components after demolition, tracking technologies are integrated to enable the effective reuse or recycling of the elements. This supports resource circularity by improving the transfer of materials, the ability to track, and transparency (Minunno et al., 2018).

There are numerous and substantial advantages to using circular design principles in construction. These strategies improve the effectiveness of resources and result in cost reductions through lower costs for material procurement, discarding waste, and generating energy (Rahla et al., 2021). They also decrease the environmental impact of building processes by reducing resource consumption, waste production, and greenhouse gas emissions (Eberhardt et al., 2020b). Additionally, circular design strategies support environmentally friendly building methods that support sustainable development in the construction sector and are in line with the environment's targets. They maximize the use of available materials while also promoting their reuse, which reduces waste production and the costs of disposal and new purchases (Torgautov et al., 2021). Additionally, by consuming less energy and producing fewer emissions, and having less carbon footprint in general, these strategies limit their impact on the environment (Torgautov et al., 2021). Circular design principles support sustainable development over time by increasing the lifespan of building parts. Adopting these ideas also ensures dedication to changing laws and guidelines regarding responsibility for the environment and sustainability, and it creates innovation and creativity in building methods, materials, and technologies (Minunno et al., 2018).

### **2.2.3 Integration of Circular Economy Principles in Prefabricated Concrete Construction**

The integration of Circular Economy (CE) principles in prefabricated concrete construction represents a transformative approach to sustainability in the construction industry. The following explores the factors necessary for successful integration, effective strategies and guidelines, and methods for recyclability assessment.

#### **2.2.3.1 Factors for successful integration**

A more comprehensive and sustainable approach is being adopted by the concrete construction industry through the integration and implementation of Circular Economy (CE) strategies. Circular Economy principles emphasize the need to take into account the full lifecycle of concrete, from production to destruction, recommending an overall systemic approach over distinct reduction strategies (Marsh et al., 2022).

The effectiveness of Circular Economy strategies is significantly shaped by external variables. The effectiveness and consequences of these strategies are influenced by the political, economic, social, technological, environmental, and legal (PESTLE) environment. Recognizing these subtleties is crucial for customized implementation and integration initiatives. Some propose to reduce overall resource consumption through unusual transformative approaches, while others support small-scale adjustments within the current political-economic systems to increase resource efficiency (Marsh et al., 2022).

Circular Economy principles are challenging established economic models in the construction sector and promoting a move toward service-oriented models that put an emphasis on creating value and the effectiveness of resources. In order to preserve value across the concrete lifecycle, creative company strategies are needed to alternate traditional product-oriented approaches with models that emphasize reuse and recycling (Marsh et al., 2022).

When putting Circular Economy strategies into practice, public approval and thoughts are also very important. Construction is a traditional sector, so increasing stakeholder education and Circular Economy consciousness is essential. For the Circular Economy actions to be successfully implemented and widely adopted, it is imperative that specialists and the public support them by handling their worries (Marsh et al., 2022).

When implementing Circular Economy strategies in concrete construction, technical considerations are crucial. When designing structures for recycling or reuse, it's important to take longevity, interaction with modern technologies like 3D concrete printing, standardization, and other factors into account. The significance of responsible decision-making as well as communication among all parties involved is demonstrated by the technical choices made during the design stage, which can lead to possibilities of circularity later on (Marsh et al., 2022).

In the concrete industry, environmental effects in particular, carbon emissions have received a lot of attention. Nevertheless, a more comprehensive assessment of environmental challenges like the extinction of habitat and decreased biodiversity is required by the principles of the Circular Economy. In order to balance conflicting priorities and accomplish general sustainability objectives, compromises might arise and appropriate decision-making is necessary (Marsh et al., 2022).

In addition, legal frameworks are essential to driving the circular economy. An accepting legal framework must include regulations for the transfer of information, liability agreements, and the recertification of recycled elements for reuse. To create and implement laws that support the principles of the circular economy while focusing on potential obstacles and difficulties, legislators, business stakeholders, and legal professionals must work together (Marsh et al., 2022).

### 2.2.3.2 Strategies & Guidelines

A variety of guiding principles can be used to integrate Circular Economy (CE) strategies into the building sector, thereby promoting resource efficiency and sustainability across the entire construction project lifecycle. According to Akhimien et al. (2022), the basic strategy is to reduce waste in the building process and encourage a lean manufacturing process. Reducing waste and utilizing prefabrication processes are two ways contractors can accomplish this (Lei et al., 2018).

Material wastage can be greatly decreased and production processes can be streamlined by using lean production techniques, such as pre-assembling plumbing fixtures and using casting molds for concrete columns (Son and Tien 2024). The incorporation of waste, substances, and scrap into newly developed parts is another essential factor. Whenever possible, recycled materials should be able to be used in place of raw materials according to the project's requirements (Verhagen et al., 2021).

Crushed rock can be used for water drainage, recycled concrete for roadways, and recycled wood for walls that aren't structural. Moreover, sustainability can be improved by emphasizing the reuse of replacement parts or entire elements (Minunno et al., 2018). For large parts, using a "supply, install, maintain, and remove" contracting strategy guarantees servicing and makes removal simple for remanufacturing (Moreno et al., 2016). This method works especially well for appliances like pumps and elevators. It's also critical to design buildings with flexibility in mind when they're in use (Wu et al., 2019).

During the building's lifespan, different requirements can be accommodated by utilizing the flexible internal space usage provided by adjustable lightweight steel-frame walls and easily accessible service risers. It's also essential to design for disassembly in order to facilitate reuse (Crowther (2022; Eberhardt et al., 2018). Buildings can be deconstructed instead of being demolished with the help of collaborative building information modeling (BIM) models, which can support deconstruction techniques (Denis et al., 2018). Project documents should include documentation of the dis-

assembly procedures for later use. It's also essential to design with the recycling of building materials in mind. It is essential to facilitate material division during disassembly in order to ensure that materials that are not appropriate for reuse can be recycled (Zi-Qiang et al., 2015). Materials can be sorted into the proper recycling streams with the help of prefabrication methods (Hrdina & Zülch 2017).

Finally, it's critical to put platforms in place to track materials and parts across their supply chain. Buildings can function as material banks at the end of their lifecycle by using barcoded elements (Denis et al., 2018). The effectiveness with which CE is implemented is improved by integrating barcoded BIM models with project management tools (Denis et al., 2018). Following these recommendations will help the building industry decrease waste, encourage recycling and reuse, and move toward a more sustainable circular economy model all of which will help protect the environment and conserve resources (Minunno et al., 2018).

### 2.2.3.3 Recyclability Assessment

In order to assess opportunities for recycling materials employed throughout building construction, highlight sustainable design, and meet the principles of the Circular Economy, a recyclability assessment is crucial in the construction of prefabricated concrete structures (Tan et al., 2020).

Roithner et al. (2022) introduce the concept of Relative product-inherent recyclability (RPR) as an assessment method to evaluate the recyclability of prefabricated concrete construction. This method considers factors such as building complexities, number of components, and the ease of disassembly to determine the fundamental recyclability of a building. In order to assess recyclability, it evaluates elements such as building complexities, number of components, and possibility of disassembly (Adams et al., 2017; Roithner et al., 2022).

Through building design optimization for simpler disassembly and recycling, the RPR assessment finds potential to increase recyclability. Moreover, it recommends changes to allow for the reuse of concentrated materials, improving the material's all-around recyclability (Roithner et al., 2022).

The RPR metric has several applications at the EU stage, including standardizing construction parts, integrating with digital building logbooks, monitoring sustainable building projects, and establishing bare minimum recyclability demands for new construction projects. To successfully control the RPR metric and develop circular building design methods, stakeholders including legislators, builders, and designers must be involved (Roithner et al., 2022).

## 2.3 Challenges and Barriers to Circular Economy Implementation in Construction

This section provides a thorough analysis of the numerous barriers preventing the construction industry from implementing the principles of the circular economy. It addresses regulatory and policy gaps, economic barriers, and cultural and organizational challenges as the main barriers. Reaching long-term sustainability goals in construction necessitates dealing with these obstacles in order to promote a shift towards circular practices.

### 2.3.1 Analysis of policy challenges

The construction industry faces several regulatory and policy barriers that hinder the adoption of circular economy principles and restrict the shift towards more sustainable and efficient behaviors.

Several studies have identified a significant challenge, which is the absence of comprehensive regulatory frameworks designed to facilitate circular economy practices, particularly in the construction sector. Although current laws prioritize the efficiency of resources, they frequently neglect to consider the sudden requirement to lower resource demand and promote circularity in the building process (Hossain et al., 2020b). This regulatory gap is a major obstacle because it prevents businesses from adopting the circular economy in its entirety, which prevents the industry-wide change required for sustainable development (Charef et al., 2021).

Furthermore, because of worries about conformity as well as potential risks, strict regulations may unintentionally inhibit innovation in sustainable technologies and construction techniques (Charef et al., 2021). This regulatory stiffness highlights how crucial it is to create an environment that is supportive of the adoption of circular economy practices by carefully balancing regulatory requirements with the need for innovation and sustainability (Purchase et al., 2021).

A vital policy issue facing the construction industry is the slow execution of waste management strategies. Even when regional governments approve such plans, the promotion of recycling initiatives and the reduction of waste generation may be restricted by the slow execution of the plans (Charef et al., 2021; Purchase et al., 2021). To tackle this issue and progress the industry's circular economy goals, it is critical to enhance execution protocols and stakeholder involvement (Charef et al., 2021).

In addition, an important barrier to the broad implementation of circular economy plans in the construction industry is the shortage of supportive encouragement and funding (Mhatre et al., 2023; Purchase et al., 2021). Companies may be unwilling to spend money on circularity even though there are possible long-term benefits if there are no outward rewards or motivations for sustainable practices (Mhatre et al., 2023). Therefore, in order to overcome this regulatory challenge, strengthening gov-

ernment encouragement through focused policies and financing processes becomes essential (Charef et al., 2021).

### 2.3.2 Economic Implications and Barriers

Circular economy principles must be applied in the construction sector if sustainable development is to be achieved, but there are a number of financial obstacles standing in the way. These obstacles include high expenses, market conditions, regulatory observance, technological limitations, and the lack of appropriate business models.

The considered increased initial expenses of implementing sustainable building practices are one of the main economic barriers (Charef et al., 2021). It can be difficult to defend investments in environmentally friendly materials and technologies because construction companies frequently have limited funding (Charef et al., 2021). Furthermore, the costly nature of material restoration technologies discourages businesses from integrating them into their operations (Purchase et al., 2021). Additionally, insufficient waste utilization and recycling technology may result in high procurement expenses for recycled materials, preventing their broad use in building projects (Purchase et al., 2021).

Important economic barriers are also presented by valuing and market conditions. Pricing structures are impacted by the lack of demand for sustainable building supplies or products, which makes it difficult for suppliers to stand for the higher prices of environmentally friendly substitutes (Charef et al., 2021). Moreover, construction companies that aim to integrate sustainable practices into their actions face difficulties due to market uncertainty surrounding the accessibility of recycled materials (Purchase et al., 2021). The limited availability of markets for recycled products makes this uncertainty worse (Mhatre et al., 2023).

In the construction industry, return on investment (ROI) is a major factor in the process of making decisions. If circular economy initiatives don't show quick profits or obvious financial advantages, businesses might be skeptical about investing in them (Charef et al., 2021). This avoidance is caused by the construction industry's preference for quick financial results and returns over social and environmental considerations (Arup & Bam, 2017). Furthermore, the absence of distinct economic benefits or incentives for environmentally friendly behaviors makes the circular economy approach less attainable from a financial perspective since businesses may put immediate cost savings ahead of long-term environmental advantages (Charef et al., 2021).

Economic barriers are further compounded by the costs of observing regulations. Construction projects might face additional costs to comply with environmental regulations and legal requirements, placing further pressure on already limited funds and discouraging spending on sustainable practices (Charef et al., 2021). Furthermore, the implementation of circular economy strategies is hampered by the lack of

regulatory frameworks designed specifically to support circular economy techniques in the construction sector (Hossain et al., 2020b).

Limited infrastructure and technology present further economic challenges. The shift to circular practices in construction is impeded by the limited infrastructure and technological developments for effective material recovery, reuse, and recycling (Mhatre et al., 2023). The rarity of proper technology and infrastructure makes it more difficult to maximize resource efficiency and reduce waste production.

The implementation is also more difficult because of the lack of appropriate circular business models designed specifically for the construction sector. The movement towards circularity in the construction industry may not be completely supported by current frameworks, which present difficulties like the requirement to create new business models (Adams et al., 2017; Hossain et al., 2020b).

### **2.3.3 Cultural and Organizational Challenges Hindering Adoption**

There are organizational and cultural obstacles associated with implementing circular economy concepts in the construction sector. These difficulties may have a big influence on how successfully construction companies implement sustainable practices.

In the construction industry, where traditional procedures tend to emphasize productivity and affordability over sustainability and circular economy principles, resistance to change is a common cultural challenge (Charef et al., 2021). This opposition is caused by a deeply rooted mentality within the organization, an ancient dependency on linear procedures, and a refusal to accept new ideas (Purchase et al., 2021). It will take a substantial cultural shift in favor of innovation, sustainability, and long-term environmental goals to overcome this resistance. Businesses need to develop a culture that considers sustainability as a fundamental value and incorporates ideas from the circular economy into their processes for making decisions (Mhatre et al., 2023).

The adoption of circular economy principles in construction has become more difficult by opposition from management and decision-makers. Resistance on the part of management to fund circular activities, value environmental concerns, or promote sustainable methods may delay the shift to a circular economy (Mhatre et al., 2023). According to Charef et al. (2021), implementing a circular economy successfully involves dealing with management resistance and promoting an innovative and sustainable culture.

Furthermore, adopting the principles of the circular economy faces challenges because of the construction industry's complex, slow, and unchanging framework (Gerceker & Pável, 2022). The sector's businesses have traditionally used linear

approaches, making the transition to circular practices challenging. The industry's resistance to the quick acceptance of circularity can be attributed to the effort and dedication required to change long-standing organizational structures, collaborations, and decision-making procedures. A slow movement towards the principles of the circular economy is essential due to the complicated structure of the industry (Gerceker & Pável, 2022).

The difficulty of resistance to change is made worse by stakeholders in the construction industry's lack of knowledge and guidance regarding the principles of the circular economy (Purchase et al., 2021). It's possible that many businesses and employees lack access to sufficient training on the fundamentals and advantages of circular economy practices. The attempts to promote organizational change toward circularity are made difficult by this ignorance. Establishing a foundation of expertise and comprehension within the industry requires outreach and education efforts (Charef et al., 2021).

Successful application of circular economy principles in construction requires cooperation and communication between stakeholders (Mhatre et al., 2023). Disparities in communication and isolated decision-making may affect accurate sustainability plans. Solving these obstacles and making sure that everyone is working toward shared sustainability objectives requires developing a culture of cooperation and transparent communication (Charef et al., 2021).

In order to promote a cultural shift in the construction industry in the direction of sustainability, organizational encouragement, and leadership are essential (Mhatre et al., 2023). Addressing organizational and cultural obstacles to the adoption of circular economy principles involves strong leadership that promotes sustainability, establishes specific objectives, and provides opportunities to implement sustainable practices (Charef et al., 2021).

Lastly, the extended duration of construction poses an additional barrier to the implementation of circular economy principles in the construction sector (Gerceker & Pável, 2022). Because buildings and constructions have long lifespans, recycling, and reusing procedures are difficult to implement. It is imperative to discover sustainable approaches for material management during the construction life cycle in order to encourage circularity in the sector.

### **2.4 On-site Assembly and Disassembly Practices of Prefabricated Concrete Buildings**

This part examines the installation and disassembly of prefabricated concrete components, with a focus on their alignment with the circularity concept and the potential for these practices to contribute to or reduce carbon emissions.

## 2. Literature Review

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Prefabricated concrete building components undergo a two-part construction process involving off-site production and on-site assembly (Xie et al., 2021). The assembly processes of prefabricated concrete building components involve a systematic approach that integrates off-site production and on-site assembly to create efficient and sustainable structures.

The assembly of prefabricated concrete components is a critical stage that influences the overall structural integrity and performance of the building and reusability potential. Various connection schemes are utilized in the assembly of prefabricated concrete components, focusing on connecting stressed steel bars and casting concrete or grout at joints (Wu et al., 2022).

The construction industry is currently witnessing improvements in on-site assembly and disassembly of prefabricated concrete components through the introduction of advanced technologies and techniques. According to Li et al. (2014), the integration of technologies like GPS and RFID can significantly improve the efficiency of prefabricated construction methods. Current practices in on-site assembly and disassembly of prefabricated concrete components involve a range of considerations that impact sustainability, safety, efficiency, and cost-effectiveness (Eberhardt et al., 2019). Moreover, prefabricated solutions with easier-to-use connections that allow for disassembly support future deconstruction and reuse, further promoting environmental sustainability (Martins et al., 2023). For instance, Wang et al. (2022) developed a model for recognizing hoisting activities using inertial measurement units (IMUs) and algorithms, achieving a high level of accuracy at 93.03%. This study identified optimal sensor positions for collision analysis, providing valuable insights for enhancing construction safety.

Sustainability of prefabricated buildings is a key focus area, with research emphasizing the environmental impact and life cycle assessment of these structures (Tsikaloudaki et al., 2022; Wang et al., 2022). Although the greenhouse gas (GHG) emissions in the construction industry are primarily influenced by two main components: the processing of raw materials for buildings and infrastructure, which accounts for around 30% of total annual construction emissions (mainly cement and steel), and the operations of buildings, which accounts for approximately 70% of emissions (Benachio et al., 2021). Hui et al. (2021), reveals that the carbon emissions in the production stage account for 97.5% of the total carbon emissions of the entire construction process, while the transportation and assembly stages account for less than 3%. Consequently, reducing carbon emissions at the production stage has received considerable attention.

The environmental implications of on-site assembly and disassembly practices in prefabricated concrete construction are minimal, however multifaceted. For instance, inadequate management of resources such as labor and machinery, as well as inefficient production, transportation, and on-site assembly of prefabricated components, can lead to higher energy consumption (Ji et al., 2020; Shen et al., 2019).

### 2.4.1 On-site Assembly Practices

**Planning and Design Integration:** The assembly process begins long before the components reach the construction site. Detailed planning and integration with the design phase ensure that the components fit perfectly, minimizing on-site adjustments. This involves using 3D modeling and simulation tools to predict and solve potential assembly issues.

**Transportation and Logistics:** The transportation of large, prefabricated components to and from the construction site can result in significant carbon emissions, especially if the distances involved are substantial. Moreover, inefficient assembly and disassembly practices that require multiple trips can exacerbate this issue, undermining efforts to reduce carbon footprints. For instance, Wang and Sinha (2021), reported a 12% rise in energy consumption was observed due to the transportation of precast components for prefabricated buildings, with an average prefabrication rate of 57%.

**Lifting and Positioning:** The placement of heavy prefabricated components typically requires the use of cranes. It is essential to guarantee precision during this stage to correctly position the components according to the design specifications. Technologies that enhance accuracy, such as GPS and laser-guided systems, are becoming more widely used (Akinradewo et al., 2021). These technologies streamline the construction process and minimize errors in component placement, leading to increased project efficiency and quality (Maas & Eekelen, 2004).

**Connection Techniques:** Connecting prefabricated components on-site is a critical step that affects the structural integrity and performance of the final construction. Moreover, it is necessary to develop prefabricated solutions that have a reduced environmental impact, going beyond the optimization of cement consumption. These solutions should include connections that are easy to use, maintain, and disassemble, facilitating future deconstruction and reuse (Martins et al., 2023). Various connection techniques are used, including bolted connections, welding, and the use of post-tensioning systems. The choice of connection method depends on the design requirements, the type of components, and the specific conditions of the construction site.

**Reduced Construction Time and Emissions:** Onsite installation and disassembly practices that are optimized can significantly reduce the time required for construction and demolition processes. This efficiency not only reduces labor costs but also minimizes the carbon emissions associated with prolonged construction activities, such as those from machinery and transportation of materials. According to Benachio et al. (2021), the principle of minimizing non-value-adding activities and increased process transparency during onsite activities demonstrated the greatest degree of interaction with circular economy practices. The efficiency of the installation process seems to be diminished by a considerable degree, as almost 71.0% of the carbon emissions stem from non-value adding activities. Implementing lean management practices in the installation cycle could potentially decrease these emissions

(Babalola et al. 2019; Ramani & Ksd, 2019; Bajjou & Chafi, 2018).

**Digitalization and Traceability:** Leveraging digital tools, such as Building Information Modeling (BIM) and material passports, can improve the traceability of materials and components throughout their lifecycle. Integrating intelligent technologies and data management platforms, such as Building Information Modeling (BIM) and advanced assembly analysis tools, can improve the efficiency and accuracy of on-site assembly practices. Construction teams can optimize the assembly process, minimize errors, and reduce material waste by leveraging these technologies (Amid et al. 2022)

### 2.4.2 On-site Disassembly Practices

**Deconstruction Planning:** Disassembly is a vital aspect of construction and demolition waste management. It is important to differentiate between the processes of deconstruction and demolition. While the term demolition refers to the careless destruction of a building, deconstruction involves the selective dismantling of materials or components for purposes of reuse or recycling in another context (Cai, & Waldmann, 2019). Similar to assembly, the disassembly of prefabricated concrete components requires careful planning. The goal is to minimize damage to the components so they can be reused or recycled. Detailed deconstruction plans are developed, specifying the sequence and methods of disassembly.

**Selective Disassembly:** The disassembly process often involves selectively taking apart components in a way that preserves their integrity (Odenbreit & Kozma, 2019). This requires a thorough understanding of the construction and connection methods used during assembly. However, the onsite disassembly of prefabricated concrete components can be challenging due to their weight, size, and the need for specialized equipment. If not managed properly, this can lead to damage to the components, reducing their potential for reuse or recycling (Odenbreit & Kozma, 2019).

In conclusion, the construction industry's shift towards prefabrication, particularly with concrete components, aligns with broader sustainability goals and the principles of the circular economy. Comparing the current practices of on-site assembly and installation of prefabricated concrete components with circular economy principles reveals both alignments and areas for improvement. Integrating intelligent technologies and data management platforms, such as Building Information Modeling (BIM) and advanced assembly analysis tools, can improve the efficiency and accuracy of on-site assembly practices (Sinenko et al., 2020). Although, certain circularity use cases call for data that BIM and IDS (Information Delivery Specification) cannot provide. For instance, information on component connections, end-of-life estimates, and disassembly instructions are somewhat hard to convey in BIM (Primasetra et al., 2022). Construction teams can optimize the assembly process, minimize errors, and reduce material waste by leveraging these technologies, aligning with circularity principles (Štverková & Václavík, 2017). However, challenges remain in terms of planning, optimization, and the economic viability of these practices. By op-

timizing logistics operations, transportation routes, and on-site material handling, construction projects can decrease their carbon footprint and work towards carbon neutrality (Chen et al., 2022).

### **2.5 Recyclable and Reusable Strategies in Prefabricated Concrete Construction**

Globally, It is estimated that concrete waste accounts for 30-40% of the total solid waste generated worldwide, with a global generation of around 4.5 billion tons per year (Marvila et al., 2022). The primary obstacles impeding the sustainability of construction projects involve the preservation of natural resources and the creation of construction and demolition waste. Prior research has revealed that these challenges stem from the insufficient information that construction project stakeholders possess regarding the appropriate management of building materials throughout their various lifecycle stages (Yu et al., 2018).

Waste reduction can be achieved through the reuse, reduction and recycling of materials, which decreases the amount of waste that needs to be disposed of and released into the environment. Reprocessing used materials into new ones involves directly reusing waste materials in their original or slightly modified form. For construction waste, recycling and reusing is the most viable option when reduction is not possible (Low et al., 2020).

#### **2.5.1 Reduction**

In Europe, concrete waste alone contributes about 30% of the total mass of solid waste. In 2016, each EU inhabitant generated 5.0 tonnes of waste, resulting in a total of 2 538 million tonnes. Unfortunately, only 37.8% of this waste was recycled in the EU that year (Chioatto & Sospiro, 2023). According to the European Union, reducing rather than starting production of construction and demolition waste would be the best course of action. The first approach, named "reduce," aims to minimize the quantity of construction and demolition concrete waste produced initially. This can be accomplished by implementing effective planning and design, optimizing material usage, and employing efficient construction practices, as suggested by Zhao and Huang (2017).

#### **2.5.2 Reuse and Repurposing**

Reuse, as noted by Bullen and Love (2011), involves extending the lifespan of buildings by altering their usage while maintaining the fundamental construction. This approach enhances both operational and commercial efficiency while reducing construction waste and conserving natural resources (Kyaw et al. 2023 ; Tan et al.

2014). Moreover, the recycling of existing concrete components from outdated structures, as examined by Küpfer et al. (2022), presents a significant opportunity to decrease the ecological impact of new construction projects. Repurposing discarded building materials is crucial to enhancing the competitiveness of the construction industry and promoting sustainable construction practices (Pronk et al., 2022). By standardizing materials for reuse, component reuse can be an effective approach in this regard, according to Webb et al. (2000).

### 2.5.3 Recycling

Recent research indicates that the recycling of concrete, particularly for the production of prefabricated components, may significantly reduce greenhouse gas emissions and the need for land use change (Zhang et al., 2018). Recycling concrete offers numerous benefits to the industry, the environment, and society. By recycling concrete waste as aggregate material, it lessens the demand for natural resources and diminishes reliance on landfill spaces (Cai & Waldmann, 2019). The study by Silva et al., (2016) assesses Eurocode provisions for recycled aggregate concrete, while Collery et al., 2015 support the use of recycled coarse aggregates in concrete mixtures for structural purposes. Their findings indicate that using 50% recycled aggregates in a concrete mix meets specific requirements for structural applications, which aligns with the maximum amount of recycled aggregates allowed in concrete according to EN standards. However, this provision restricts the recycling potential of concrete demolition waste, as stated by Grigoriadis et al. (2019). Although it typically saves substantial resources, recycling is positioned at the bottom of the 3Rs hierarchy as it also entails the consumption of additional materials and fuels. For example, concrete must be cleared of steel reinforcement bars and other contaminants before it can be crushed into gravel. In order to transform gravel into new concrete, additional cement, water, and sand are required (O’Grady et al. 2021).

# 3

## Methodology

This study aimed to explore how on-site assembly and disassembly practices of prefabricated concrete buildings differ from circular economy principles and impact greenhouse gas emissions reduction. To address this inquiry, it was essential to examine the concepts of circularity and sustainability of prefabricated concrete construction techniques and analyze their interactions. This study employs a thematic approach in its literature review. According to Clarke and Braun (2013), thematic analysis is a method of recognizing patterns and developing themes through extensive reading on the subject.

The methodology adopted for this study was created to offer a thorough comprehension of the subject importance by employing qualitative methods of study. In order to fully understand the complex issues related to prefabricated concrete construction, environmental sustainability, and circular economy principles, qualitative research was selected for this study. This method allows for the collection and analysis of extensive information, enabling the exploration of diverse perspectives and experiences of industry stakeholders (Drisko, 2005; Cresswell & Porth, 2016).

The literature review and empirical data were collected and examined simultaneously, employing an abductive methodology. By integrating theoretical knowledge with empirical evidence, this approach facilitated the development of fresh theories and insights (Timmermans & Tavory, 2012). To conduct a thorough literature review, various search engines such as Science Direct, Google Scholar, and Scopus were utilized. Relevant academic articles, books, reports, and other scholarly sources were identified using keywords such as "prefabricated concrete," "circular economy," "strategies," "assembly and disassembly," "recyclable and reusable," "sustainability," and "challenges". This systematic approach ensured a comprehensive examination of current understanding and industry best practices (Bryman, 2016).

Semi-structured interviews were conducted with multiple stakeholders involved in prefabricated concrete construction, including the business development manager, project manager, sustainability manager, and production manager. This strategy made it possible to gather a variety of viewpoints and insights from people with different positions and responsibilities within the sector. Interviews were performed either in-person or virtually, based on the participants' preferences and availability.

During the study process, ethical considerations were of the highest priority. Before the interviews, informed authorization was requested from every participant,

### 3. Methodology

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guaranteeing anonymity and confidentiality to ensure the interviewees' comfort and freedom to speak transparently and freely. The freedom to leave the research at any moment and without consequence was guaranteed to the participants. Transparency, reflective thinking, and the triangulation of data sources were further measures taken to retain the reliability and honesty of the research findings (Cresswell & Porth, 2016).

# 4

## Empirical Result

As part of our study, we conducted interviews with professionals in the construction industry, selecting our participants based on their diverse experience and involvement in roles related to sustainability, project management, and circularity. This section will present the findings gathered exclusively from the information provided by the interviewees. A total of 30 individuals were contacted, and 4 agreed to be interviewed. All of the interviews were conducted digitally, with an average duration of 30 to 60 minutes per respondent.

### 4.1 On-site Assembly and Disassembly Practices

According to the respondents, typical onsite assembly practices involve planning and scheduling with various stakeholders, such as manufacturers, subcontractors, logistics, as much of the work involves transporting, receiving and lifting prefabricated concrete components into position. Although Respondents 1 and 2 have limited experience with onsite assembly, however respondents 3 and 4 described onsite assembly;

*As an approach entirely different from the traditional method of construction. With prefabrication, concrete components like slabs, columns, walls and beams, are produced at a place/yard offsite and shipped to site with heavy trucks and lifted into position using cranes. Once the substructural elements have been installed, the components are lifted into position with the aid of cranes, and quality control is performed before they are placed.*

All the respondents emphasize the significance of planning and scheduling when dealing with prefabricated components. This is to prevent the installation of unnecessary components, which can slow down work progress, waste resources, and compromise the integrity of connections if installed multiple times.

*“As a project leader, I would emphasize the significance of having all necessary resources and materials on-site, in a timely manner. It is crucial that construction elements arrive precisely when they are scheduled to, so that the project can progress efficiently and without unnecessary delays. To ensure this, it is vital to prepare accordingly, well in advance, and to ensure that all necessary materials are readily available (Respondent 3). This includes adhering to the specified time schedule provided by the supplier, so that the construction process can proceed seam-*

*lessly, without any hindrances or delays. Proper planning and organization are key to achieving successful assembly and project outcomes (Respondent 4)''.*

Respondent 3 stated that the development of technologies like QR codes, BIM, and RFID has greatly simplified and streamlined the assembly process. Despite not using it in their current project, they also believe that these technologies will facilitate the creation of a comprehensive database of components, which can be easily accessed and evaluated for future reuse. Conversely, respondent 4, expressed the view that their current practices do not adhere to the principles of circularity. According to them, they rarely utilize BIM or QR codes during the onsite assembly of prefabricated components, as they are a small company.

The participants in the study indicated that they had limited experience with the disassembly of prefabricated concrete components, as this is not a frequent or conventional practice. Although it is customary to salvage or disassemble windows, doors, toilets, and bricks, the disassembly of concrete components is not common due to the fact that most buildings are not designed for this purpose. The assembly practices of prefabricated components are repetitive, and the question of how and when the components are delivered to the site is critical in minimizing waste, maintaining integrity, and ensuring safety.

## 4.2 Recyclable and Reusable Strategies

The order of precedence for recyclability and reusability of components is determined by the process of assembly and disassembly, which typically occurs at the end of a component's lifecycle. However, all respondents unanimously agreed that stakeholder intentionality is necessary to facilitate the reuse of prefabricated components, particularly by incorporating it into the early design phase. While respondent 2 acknowledged that they sell buildings and apartments with disassembly instructions, respondent 4 indicated that they had not been involved in the disassembly of buildings.

Respondent 3 described a specific instance in which they retrieved components from an old building and repurposed some of these components in a new project:

*''We started with thorough examination and inventory of building components, assessing reusability and repurposing potential. A comprehensive list was compiled, specifying quantities such as doors, with attention given to optimal quality to ensure efficient utilization of resources. Subsequently, the deconstruction process ensued, culminating in transportation of materials to a designated storage facility, close to the site of the new school project. Furthermore, respondent 3 stressed that the process would have been more efficient, if the utilization of QR codes was deployed for enhanced client visualization, which has been explored by another company, facilitating clients to view the process through an interactive digital platform''.*

In addition, respondent 1 says that there recyclability and reusability strategies is client dependent;

*"Our approach to projects is guided by the needs and objectives of our clients. We engage in dialogue with them to understand their goals for the building in question. The nature of the project therefore varies depending on the client's requirements. Some clients have a strong focus on sustainability and circularity, while others may not know where to begin. In such cases, we provide our expertise and suggest solutions based on their preferences. For example, one of our clients has a very strong commitment to sustainability and circularity, and we have established a company-wide circularity routine to support these efforts."*

An important part of these strategies is about using materials efficiently and creating circular resource flows through reuse and increased material recycling. Respondent 1 indicated that they have initiated the measurement of construction project quality using the Project Quality Index (PQi). This index adopts a comprehensive approach to evaluating project quality and aims to identify potential risks in the initial stages. The construction industry's primary contribution to climate change stems from the production of materials, which is evidenced by the fact that the building material (frame) accounts for 98 percent of the emissions in our climate accounts. There are several significant obstacles that must be overcome in order to minimize the industry's environmental impact. To address this issue, our focus is on increasing the use of recycled materials, minimizing construction waste, and exploring alternative building materials with a lower carbon footprint. To be able to follow up and steer towards the goal of climate neutrality, we have been preparing an annual climate report since 2022, in accordance with the GHG Protocol. Our interim target is to reduce emissions intensity by 5% per year.

On the contrary, respondent 4 emphasized that, given their current on-site assembly practices, it would be challenging if not entirely impractical to reuse or repurpose the prefabricated concrete component due to the manner in which they are connected on-site.

*"The present on-site connection involves pouring wet concrete internally within the components, making it concealed, and necessitating the breaking or forcing of the component at the end of its lifecycle".*

### 4.3 Opportunities

Following four industry professionals' insightful interviews, a number of perspectives are revealed when examining opportunities for sustainable development in the construction sector regarding the integration of circular economy principles for prefabricated constructions. Even though each interviewee has a unique perspective, they all agree that integrating circular economy ideas into prefabricated concrete construction is a crucial step in improving sustainability and resource efficiency.

#### 4. Empirical Result

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Interviewees 2, 3, and 4 combined provide a strong recommendation of the importance of this methodology. They push for an overall change in the sector, highlighting the revolutionary power of circularity in reducing environmental effects and promoting long-term sustainability. Reusing materials from construction sites or demolished buildings, like concrete, bricks, and steel components, can help reduce waste production and decrease the need for raw materials, according to these professionals. A similar message runs through all of their statements, emphasizing a mutual solution to use the resources already in place in a more sustainable and thoughtful way.

Interviewees 3 and 4's promotion of "designing for disassembly" serves to strengthen this viewpoint. They argue that the construction industry can adopt a genuinely circular approach if structures are designed with future reuse in mind. This innovative design concept encourages the constant reusing and reintegration of materials into the built environment, contributing to a culture of regenerating in addition to resource efficiency.

In this context, interviewee 1 highlights the observable advantages of employing recycled materials, providing scenarios where this strategy has resulted in notable savings in terms of time, money, and the impact on the environment. Their example highlights the useful benefits of implementing circular economy ideas and shows how sustainability and profitability can meaningfully overlap.

Interviewee 2 adds a strategic perspective to the conversation by emphasizing how technological advancements and government assistance may encourage the integration of circular economy principles. Their vision goes beyond the construction industry itself, imagining a larger ecosystem in which innovations in technology and policy frameworks work together to drive the industry toward greater sustainability.

Interviewee 3 highlights the significance of collaborative governance structures and stakeholder engagement in creating an ideal environment for circular economy efforts. Through linking government organizations and clients around a common understanding of sustainability, they promote the development of an ecosystem in which circular practices are not only welcomed but also actively rewarded.

Interviewee 4 explores the complexities of innovation and environmental impact assessment, arguing in favor of a comprehensive strategy that incorporates life cycle assessments into the decision-making process. Their response emphasizes the value of continuous enhancement and data-driven insights, highlighting innovation as an essential driver of sustainable development in the building sector.

When taken as a whole, the perspectives offered by these interviewees create a thorough picture of the advantages that come with integrating circular economy concepts into prefabricated concrete construction. Despite having different points of view, they are united by an identical dedication to sustainability, which high-

lights their shared goal of creating a future for the construction industry in general. An industry that is more resource-efficient, adaptable, and environmentally friendly.

## 4.4 Challenges and solutions

According to the interviewees, there are multiple challenges in the way of integrating circular economy principles into prefabricated construction. As Interviewees 1, 3, and 4 have demonstrated, client preferences are a common thread that influences material choices and the adoption of sustainable practices. Furthermore, as mentioned by Interviewee 1, the lack of a centralized database for reusable components makes it harder to find appropriate materials, which is made worse by insufficient storage facilities.

Interviewee 2 elaborates on these difficulties, highlighting the financial expenses related to disassembling, cleaning, testing, and shipping recycled materials. Furthermore, as indicated by Interviewees 2 and 3, policy changes are required due to regulatory restrictions, which include the categorization of materials that are preserved in storage as waste. These limitations make it difficult to manage and reuse resources efficiently.

A noteworthy obstacle mentioned by Interviewee 2 is the resistance of organizations to adopt new materials or procedures, like concrete with enhanced climate properties. Because integrating circular economy principles into construction projects requires acceptance from a variety of stakeholders who might be hesitant to step away from traditional methods, resistance to change can be a challenge.

Key obstacles are logistical ones, like Interviewee 4's assessment that present assembly procedures do not align with circular principles. Additionally, as stated by Interviewee 4, the cost-driven competitiveness of the construction industry can make it difficult to prioritize sustainability initiatives over less expensive alternatives.

Interviewees offer various approaches to address these complicated challenges. As stressed by Interviewee 3, educating clients about the long-term advantages of sustainable practices is essential to connecting the project's objectives with sustainability goals. Interviewees 2 and 4 support cooperation among suppliers and stakeholders as a means of promoting innovation in circular construction practices and guaranteeing the quality and dependability of repurposed materials.

Government involvement, as stated by Interviewee 2, aims to change current regulations to encourage material reuse in order to establish an environment that is supportive of circular practices. Furthermore, as suggested by Interviewee 4, incorporating sustainability factors into the early stages of design can improve the adaptability of prefabricated parts for later reuse, which is consistent with the circular economy concept.

#### 4. Empirical Result

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Additionally, as Interviewee 4 pointed out, lifecycle evaluations allow businesses to evaluate the effects on the environment and identify areas for improvement. As stated by Interviewee 3, creating a culture of sustainability within organizations through education and awareness promotes dedication to environmentally friendly procedures.

Construction companies may effectively overcome the challenges and efficiently integrate circular economy principles into prefabricated construction, improving sustainable procedures within the industry, by taking a cooperative and complete approach that takes into account each of these factors.

# 5

## Analysis

In this part of the study, we examine qualitative data gathered from interviews with industry professionals to examine existing practices in the assembly of prefabricated concrete components and circularity in the construction sector. Our analysis employs thematic analysis to identify important themes and patterns that illustrate both adherence to and deviations from circularity principles. It is worth noting that the themes identified are consistent across the majority of the interviews, which can be attributed to the structuring of the research questions and the interviewees' diverse roles in the past.

### 5.1 On-site Assembly and Disassembly Practices

Effective on-site assembly and disassembly practices are crucial for the successful implementation of prefabricated construction projects. This section delves into the key aspects of planning and scheduling, technological integration, and disassembly processes that are essential to optimize the construction workflow and ensure sustainability.

#### 5.1.1 Planning and Scheduling

Our findings emphasized the significance of planning and scheduling prior to the actual installation of these components in their designated positions. Efficient planning and scheduling are essential for preventing the need for multiple installations and assemblies, which can result in rework or damage to components and waste valuable time and resources. Without this, the potential for reusing components at the end of their life cycle may be negatively impacted. The existing literature also highlighted that a high-quality result depends on a thorough design and planning basis. To reduce construction time on-site, very detailed scheduling and planning of logistics and storage in advance are necessary. The construction process for prefabricated buildings is repetitive, and approximately 70% of the time spent on construction is dedicated to assembling components (Mao et al., 2013; Xie et al., 2021). Any friction within the process chain causes significant chain reactions. A comprehensive planning phase involving collaboration between different experts is a critical part of the prefabrication process (Hanafi et al., 2017). The use of prefabricated construction systems that follow a standardized workflow from planning to production and assembly offers a wide range of benefits in terms of performance, process, and tech-

nical aspects (Lattke et al., 2013). Research has shown that having prefabricated components readily available at construction sites and ensuring crane mobility are crucial factors during on-site assembly of prefabricated components (Hanafi et al., 2017).

### 5.1.2 Technological Integration

Effectively managing project data and documentation has long been a challenge in the construction industry. One solution is the integration of technologies, which can facilitate centralized sharing and storage of construction information or data, leading to the automation of construction operations. The importance of using technologies like BIM, RFID, and QR codes in onsite assembly and disassembly of prefabricated concrete components is supported by both literature and empirical data. BIM is now extensively utilized for prefabrication-based construction in the United States, Europe, the United Kingdom, Japan, South Korea, and Singapore. It currently supports the planning, design, construction, operation, and maintenance of a wide range of infrastructures, including apartment buildings and bridges (Zhang et al., 2020). Despite being aware of its capabilities, the empirical study revealed that BIM is rarely used during the assembly, and disassembly phases of prefabricated components.

### 5.1.3 Disassembly

Previous research has generally identified the design process as the primary obstacle to building deconstruction, most especially buildings with concrete components. Buildings are typically designed without taking into account their eventual demolition and the recycling of their materials (Rios & Grau, 2015). Architects and contractors typically regard their "creations" as permanent and fail to make provisions for their eventual disposal (Rios & Grau, 2015). This is partially supported by empirical evidence, but there is now a growing trend towards designing buildings for disassembly. Some developers and contractors are now marketing buildings with deconstruction plans and instructions. Despite this, there are still challenges to be addressed in terms of scalability.

## 5.2 Recyclable and Reusable Strategies

Implementing recyclable and reusable strategies in construction is essential to advancing sustainability and fostering a circular economy. This section analyses the scalability of such strategies, stakeholder preferences, and performance and evaluation considerations.

### 5.2.1 Materials and Scalability

The need for the recyclability or reusability of concrete structures creates a paradox between durability and dismantability (Fayyad & Abdalqader, 2020; Ortlepp et al.,

2015). The trend of designing and constructing buildings with detachable connections is prevalent in structures utilizing timber and steel as construction materials (Fayyad & Abdalqader, 2020). This preference stems from the flexibility and ease of disassembly inherent in these materials, as opposed to the challenges posed by the rigidity requirements at joints typically associated with concrete construction (Allen & Iano, 2019). In the same vein, the empirical study highlighted that current practices of assembling prefabricated concrete components on-site do not allow for dismounting. However, Devènes et al. (2024) explored the potential of reusing cut concrete slabs in new buildings to achieve ultra-low-carbon floor designs. This approach resulted in a reduction of carbon emissions by 80% compared to traditional construction (Devènes et al., 2024). Although this research direction, including testing the procedure in different construction basins, has yet to be explored on a large scale, it offers new ways of reusing prefabricated components and is more suited to buildings not designed for disassembly. There is a pressing necessity to showcase the practical and financial benefits of implementing standardized ways that can be easily replicated across various construction projects.

## 5.2.2 Stakeholder Preferences

Our finding highlighted that the need and requirement for sustainability varies from one client to another. However, achieving sustainability in the construction sector goes beyond client requirements. The integration of circular economy principles can be further encouraged by advancements in technology and government support. Looking beyond the construction sector, the respondent envision a broader ecosystem where technological innovations and policy frameworks collaborate to propel the industry towards enhanced sustainability. Collaborative governance frameworks and the engagement of stakeholders are essential in cultivating an environment that is conducive to the success of circular economy initiatives (Moallemi et al., 2020; Karhu & Linkola, 2019; Jaimes-Valdez & Jacobo-Hernández, 2016). Respondents emphasize the necessity of collaboration between government agencies, construction firms, and clients to establish sustainability goals. By doing so, an environment can be created that encourages circular practices and provides rewards for their implementation.

## 5.2.3 Performance and Evaluation

According to our findings, determining the suitability of reused components for assessing and evaluating their structural integrity proved to be a difficult task. The absence of standardized code of practices for verifying the technical and mechanical properties of reusable building components impedes the growth of markets for such components. Research into design for disassembly has primarily concentrated on assessing the economic and environmental implications of reusing components in recent years (Adams et al., 2017; Bertino et al. 2021). Nonetheless, it is essential to consider the structural behavior of these components during their second life cy-

cle, as this will play a significant role in determining their suitability for widespread adoption in the construction industry. Andersen et al., (2020) conducted research to assess the structural performance of a novel design for disassembly (DfD) concrete connection. The design incorporated enhanced reinforcement continuity, ductility under loading, predictable stress distribution, and crack propagation patterns that aligned with the design's intended expectations. The study focused on moment-resisting DfD concrete connections for frame joints, while neglecting to assess the condition of other structural elements after reconstruction. Furthermore, the absence of testing on reconstructed specimens and the limited scope of DfD connection types restricts the ability to gain a comprehensive understanding of the structural behavior and its potential for reuse.

### 5.3 Opportunities and Challenges

Ensuring efficient natural resource consumption is a significant economic, social, and ecological challenge of our time, as doing so can alleviate pressure on the environment (Ortlepp et al., 2015). Adopting the circular economy principle of designing buildings for disassembly presents the construction sector with a remarkable opportunity to substantially decrease its carbon footprint contribution. This approach combined with prefabricated methods of construction, offers businesses the benefit to evaluate its environmental effects and pinpoint areas that require improvement, thereby fostering a culture of sustainability within organizations through education and raising awareness, which ultimately leads to a commitment to environmentally responsible practices. However, there are challenges that must be addressed in the field of concrete structures, one of the main being the paradox between durability and dismantability. There is also inconsistency in the expectations of stakeholders and the necessity for a more comprehensive collaboration among government agencies, construction companies, and clients to establish and achieve sustainability objectives. The advancement of technology and the establishment of supportive policy frameworks are vital for fostering an environment that encourages the adoption of circular methods. Furthermore, the construction industry faces significant hurdles in the form of regulatory and standardization issues. Due to the heavily regulated nature of the sector and its traditional approach, the implementation of innovative techniques and materials may be delayed. This is because obtaining regulatory approval and developing industry standards can be a time-consuming process. Additionally, varying legal frameworks for sustainable building practices across different countries and regions pose challenges for multinational corporations seeking to implement consistent policies worldwide.

# 6

## Synthesis

The results of the study are presented in line with the research questions, focusing on current practices and the potential for incorporating circular economy principles into the prefabricated concrete component assembly and disassembly process on-site. These findings are derived from a thematic analysis of qualitative data gathered from interviews with industry professionals.

### **6.1 Alignment with Circular Economy Principles and GHG Emissions Reduction**

disassembly practices align with circular economy principles and impact greenhouse gas (GHG) emissions reduction in several ways:

#### **6.1.1 Planning and Scheduling**

Effective planning and scheduling play an essential role in minimizing rework, preventing component damage, and reducing waste. Thorough planning supports component reusability and streamlines construction processes. This is in alignment with circular economy principles by promoting efficient material and resource utilization, thereby reducing waste and emissions. Furthermore, efficient planning GHG emissions can be reduced, by minimizing the need for multiple installations and rework, thereby decreasing emissions associated with additional material production, transportation and machinery operation.

#### **6.1.2 Disassembly**

There is a growing trend towards designing buildings for disassembly, although traditional design practices still exist and often overlook this aspect. Some developers are beginning to include deconstruction plans, but scalability remains a challenge. Designing for disassembly promotes the circular economy by facilitating material reuse and recycling, thereby extending their lifecycle. Facilitating material reuse reduces the demand for new raw materials, resulting in decreased emissions associated with material production and transportation.

## **6.2 Enhancing On-Site Assembly and Disassembly Practices**

The research unveiled some strategies to improve the efficiency of on-site assembly operations, while simultaneously promoting environmental sustainability and circular economy principles.

### **6.2.1 Technological Integration**

The integration of technologies such as Building Information Modeling (BIM), Radio-Frequency Identification (RFID), material passport and Quick Response (QR) codes has been recognized for enhancing data management and automating construction processes. However, the application of BIM in assembly and disassembly phases is currently limited. Utilizing these technologies fosters resource efficiency and enhances component lifecycle management, supporting circular economy objectives. Improved data management and automation streamline processes, reduce material waste, and lower emissions linked to manual handling errors and safety.

### **6.2.2 Stakeholder Preferences and Collaboration**

The study revealed varying levels of sustainability commitment among clients, emphasizing the need for cooperation among stakeholders, and government support to achieve broader circular economy adoption. Collaboration and supportive policies play a crucial role in fostering an environment conducive to circular practices. Effective stakeholder collaboration and supportive policies can drive industry-wide changes that reduce emissions through sustainable practices. One of the key players in the pursuit of component reuse strategies is the component manufacturers. They play a crucial role in this partnership. By including a buy-back clause in the contract, and the possibility of the manufacturer retrieving components from soon to be demolished buildings, can increase confidence and stimulate the market for reusable components.

### **6.2.3 Performance and Evaluation**

A significant barrier identified was the lack of standardized practices for verifying the technical properties of reusable components. Expanding ongoing research into the structural performance of novel designs for disassembly (DfD) is necessary. Establishing standardized evaluation methods is essential to ensure the reliability and safety of reused components, thereby supporting their broader adoption. Standardization can streamline the reuse of components, reducing the need for new material production and the associated emissions. Furthermore, it is crucial to develop a grading or reusability rating system for components or buildings, similar to building certification in BREEAM, LEED, DGNB, and other such systems, in order to assess

the circularity of the built environment. Establishing such a system is essential to ensure the sustainability and environmental friendliness of the built environment.

#### **6.2.4 Standardization**

Standardization of component design, particularly for connection interfaces, necessitates urgent attention. The implementation of uniform design standards for these connections will significantly enhance the precision and completeness of reuse component databases. This standardization facilitates the accurate capture and documentation of component specifications, which is critical for efficient disassembly, evaluation, and subsequent reuse. Embracing standardized connection designs can assist the industry in streamlining the incorporation of prefabricated components into circular economy frameworks, ensuring consistency in quality and compatibility across diverse construction projects.

#### **6.2.5 Training**

Providing training to personnel is crucial for implementing circular economy principles, with a specific focus on design for disassembly (DfD) and component reuse. Such training programs will aim to enhance understanding of circular economy concepts, emphasizing resource efficiency, waste reduction, and sustainability benefits. By developing DfD skills, engineers, architects, and construction workers can create prefabricated designs for easy disassembly and reassembly, including material selection and lifecycle planning. Training also covers implementing reuse strategies, such as assessing used components, refurbishing them, and integrating them into new projects. Furthermore, technological proficiency training on tools like BIM, RFID, and QR codes is essential for efficient component tracking and data management during disassembly and reuse. Undertaking training of this nature will likely come with a significant cost. To this end, we have recommended that the government offer incentives for initiatives that emphasize circularity, by implementing regulations that encourage this type of innovation. Furthermore, we propose that circularity principles be integrated into the broader sustainability plan.

### **6.3 Opportunities and Challenges**

The results of the study revealed a set of opportunities and challenges related to the integration of recyclability and reusability principles of the circular economy into the construction sector. The opportunities presented by this integration outweigh the challenges, as it has the potential to significantly reduce the carbon footprint of the construction industry. The opportunities and challenges will be described based on different sustainability dimensions.

### 6.3.1 Opportunities

Integrating the circular economy principle into prefabricated concrete construction provides a range of opportunities and these opportunities are in different aspects such as Environmental, Economical, and Social.

#### 6.3.1.1 Environmental

Integrating the practice of component reuse in construction offers substantial environmental benefits by optimizing resource usage and minimizing construction and demolition waste, thereby advocating for sustainable building methods. By prioritizing reusability, the reliance on unused resources is reduced, as buildings with easily removable components decrease the need for raw material extraction and processing, thereby conserving resources and lowering energy consumption. Conventional construction techniques result in substantial waste production, but designing for reusability enables the repurposing of building components, significantly reducing waste generation and prolonging material lifecycles.

#### 6.3.1.2 Economical

Evaluating buildings based on their potential for reuse at the end of their lifecycle presents significant economic opportunities in the construction industry. By assessing and certifying buildings for their ability to be disassembled and reused, their market value can substantially increase, offering a viable alternative to traditional demolition and landfill practices. Buildings designed with a high reusability potential can be marketed as valuable assets due to their lower lifecycle costs and positive environmental impacts. Owners and investors can expect higher returns on their investments, as these buildings offer extended utility over multiple lifecycles, reducing the need for new construction and associated expenses. Certifying buildings based on their potential for reuse can serve as a unique selling point, distinguishing them in a competitive real estate market. This distinction can attract environmentally conscious buyers and tenants who prioritize sustainability, driving demand and ultimately raising property values.

#### 6.3.1.3 Social

Comprehensive training programs are critical for enhancing the construction workforce's competence in reusability and designing for reusability, with a focus on innovative techniques for disassembling and reassembling building components. Enhancing the skills of the workforce can result in a more versatile team, improving job satisfaction and career advancement. Prioritizing reusability can play a significant role in preserving historical buildings by extending their lifespan through careful component reuse, preserving architectural heritage while promoting sustainable practices. To encourage widespread acceptance, construction companies should adopt new business models that incorporate reusability principles, such as establishing decentralized storage facilities for reusable components and creating job oppor-

tunities in facility management for skilled workers.

### **6.3.2 Challenges**

Assessing the potential reuse of buildings presents both economic opportunities and obstacles. Developing standardized criteria and certification processes that are widely recognized requires collaboration across the industry. Designing buildings for high reusability may involve higher initial costs due to specialized materials, which could make it difficult for stakeholders to justify the investment without clear long-term benefits. Developing business models that prioritize reusability presents companies with various challenges, including financial, logistical, and operational obstacles. Establishing decentralized storage facilities necessitates significant investments in infrastructure, while ensuring the consistent quality and availability of reusable components poses distinct difficulties. Additionally, existing regulations may not support reuse practices, which could limit the widespread adoption of this approach. Overcoming these challenges is essential to fully realize the economic and environmental benefits of building reuse.

# 7

## Discussion

A revolutionary strategy for overcoming the significant environmental impact of the construction industry is being indicated by the integration of Circular Economy (CE) principles into Prefabricated Concrete Construction (PCC). This detailed discussion assesses how PCC, when combined with CE principles, might increase efficiencies in resources, cut waste, and improve the environmental sustainability of building operations as a whole, revolutionizing sustainable construction practices.

### 7.1 Environmental Sustainability Impacts

Environmental sustainability is greatly improved by the application of PCC which complies with CE guidelines. Massive decreases in environmental damage result from this approach, which places a high priority on waste reduction and resource efficiency throughout the construction process. There is less waste produced during construction and demolition thanks to the easy disassembly, reuse, and recycling of prefabricated and modular components made for various life cycles. Moreover, the standardized manufacturing of prefabricated modules in a regulated manufacturing atmosphere improves quality control, minimizes mistakes and the requirement for on-site modification, and lessens the carbon emissions related to traditional construction processes.

Furthermore, a significant amount of energy is saved in the transportation of raw materials and onsite construction because components are produced away from the site and shipped as whole elements. By shortening the construction period and reducing emissions from construction equipment and ongoing problems at the site, the optimized method of assembly also reduces the environmental impact of extended site activities.

### 7.2 Exploring On-site Assembly and Disassembly Practices

Traditional building practices usually struggle to consider the possibility of material reuse or recycling at the end of their useful lives, which leads to substantial waste and inefficiency. On the other hand, PCC that is designed according to CE principles

takes the lifecycle effects of materials into account by default. This method greatly decreases the demand for the extraction of raw materials and minimizes waste by ensuring that components can be recycled or reused in addition to making assembly and disassembly less complicated. In the field of PCC, structured, adaptable construction using prefabricated components in controlled production environments characterizes on-site assembly techniques shifted by CE principles. This improves the accuracy and the ability of the construction parts while also reducing the environmental obstacles that are usually connected to on-site construction.

### **7.3 Strategies to Enhance On-site Assembly Efficiency**

Multiple innovative strategies are needed to increase the effectiveness of on-site assembly in the context of environmental sustainability and CE. Adopting reusable design principles speeds up construction while allowing potential flexibility and reuse of materials by enabling components to be compatible and simply assembled or disassembled. Standardizing prefabricated parts contributes even more to waste reduction by lowering overproduction and insufficient stock. By anticipating possible problems, modern digital tools like Building Information Modeling (BIM) improve planning and efficiency, maximize the utilization of materials, and decrease waste. Moreover, putting money into employee development and training guarantees that employees are knowledgeable about sustainable development principles and effective building methods, which raises the general effectiveness and sustainability of construction projects.

### **7.4 Opportunities**

By minimizing its environmental impact and increasing resource efficiency, the adoption of CE principles into PCC holds an opportunity for transforming the construction sector. By lowering the amount of waste produced and decreasing the need for raw resources, material reutilization supports global sustainability goals. Due to the decreased need for extracting raw materials and the decreased logistical demands of transporting these materials, this approach greatly decreases greenhouse gas emissions. For businesses striving to comply with ever-tougher regulations concerning the environment, as well as in the cause contrary to climate change, these reductions are vital.

Building lifecycle costs are probably going to go down from a financial perspective. Improved insulation and more energy-efficient building components and methods are the main causes of this decrease in energy usage. Adopting PCC integrated with CE principles can have financial benefits in addition to offsetting the upfront costs associated with it, such as the possibility of making money from the sale of

recycled materials or from reusing components at the end of their lives. This change helps construction companies manage their bottom line while also offering end users savings on costs, which might enhance their ability to compete in the market and increase customer satisfaction.

Furthermore, implementing these ideas might promote innovation in the planning and building phases. It pushes businesses to investigate innovative materials and techniques, creating an innovative culture that may create the way for innovations in additional aspects of the construction industry. This culture has the power to attract both brains and funding, which will accelerate the industry's growth and development.

### 7.5 Challenges

Although the advantages are obvious, there are significant obstacles to the incorporation of CE principles into PCC. The initial financial investment necessary to establish prefabrication structures that follow the CE guidelines is one of the biggest. In addition to the physical foundation, this framework requires staff training and the purchase of new technologies. The high cost is a challenge, especially for smaller businesses or those operating in developing countries where funding or capital is limited.

There are other major obstacles in the form of regulatory and standardization challenges. Since the construction sector is heavily regulated and has a history of conservatism, the adoption of new techniques and materials may take some time because of the requirements for obtaining regulatory authorization and developing standards in the sector. This slowdown is made worse by the fact that different countries and regions have different laws governing sustainable building practices, which makes it challenging for multinational corporations to apply uniform policies throughout the world.

The industry's cultural resistance makes the adoption of CE principles even more challenging. Because of their familiarity with established procedures, many construction companies and their clients may perceive developed, unproven procedures as risky. Implementing new approaches that may be more sustainable is not always preferred over maintaining traditional approaches that provide consistent results. It will take a lot of work to overcome this resistance through argumentation and education, showcasing cases that succeed and proving that CE principles have long-term advantages for the environment, business, and operational effectiveness.

Aside from cultural resistance, an actual issue is making sure that every connection in the supply chain of the construction sector complies with CE principles. Successful implementation of these principles requires the support of suppliers, contractors, and clients, which can be challenging to accomplish through coordination and cooperation.

# 8

## Conclusion

The study revealed a strong relationship between the construction of prefabricated concrete components and increased carbon emissions. Additionally, the qualitative data showed that current assembly procedures for these components often do not adhere to circular economy principles, which indicates inefficiencies and missed opportunities for sustainability. Although there are tools available to optimize the assembly process and reduce environmental impact, their adoption has been limited within the industry. This highlights the need for broader implementation and standardization of best practices to align on-site assembly methods with circular economy objectives.

Our study supports previous research that emphasizes the critical role of onsite assembly in generating carbon emissions (Kanafan et al., 2023). Our results align with the studies conducted by Yang et al. (2023) and Akanbi et al. (2018), which suggest that prefabricated concrete construction offers substantial opportunities for the construction sector to adopt circular economy principles. This method promotes sustainability and resource efficiency by facilitating the reuse and recycling of materials. However, despite these advantages, the widespread implementation of prefabricated concrete construction faces notable challenges. Scalability and standardization of components are significant hurdles that need to be addressed to fully realize the potential of this construction method. Standardizing components and processes across various projects and regions are essential to overcome these barriers and achieve broader adoption in the industry.

The results of this study have substantial implications for the construction industry in terms of economic, social, and environmental factors. Implementing our findings into onsite assembly and disassembly processes can boost productivity, leading to shorter assembly times and lower labor costs. This, in turn, can result in cost savings and enhanced competitiveness. Environmentally, more efficient processes onsite can contribute to reduced carbon emissions, aligning with sustainability objectives and stricter environmental regulations. Socially, adopting these practices can improve worker safety, reduce physical strain from extended assembly tasks, and promote job satisfaction and competence. Retraining the workforce can increase their competence and job satisfaction, resulting in a healthier and more sustainable work environment.

This study on prefabricated concrete construction within sustainability and circular economy frameworks has several limitations. The focus on PCC may limit the

## 8. Conclusion

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generalizability of findings to other construction types or materials. The literature review, while extensive, might not cover all global PCC practices, particularly those in developing countries due to limited available data. Additionally, the small sample size of interviews, with only four industry professionals participating, may not represent the broader industry. Environmental impact assessments focus primarily on greenhouse gas emissions, potentially overlooking other environmental impacts like water usage and biodiversity effects. Data accuracy and completeness on carbon emissions during production stages may also vary.

To advance the understanding and implementation of sustainability and circular economy principles in prefabricated concrete construction (PCC), several areas warrant further investigation. While this study primarily focuses on greenhouse gas emissions, future research should investigate water usage, biodiversity, resource depletion, and other environmental factors to provide a more holistic view of the sustainability of prefabricated construction methods. This comprehensive assessment will help identify additional environmental benefits or trade-offs associated with PCC, guiding more informed decision-making and policy development. Future studies should analyze life cycle costs, including initial investment, maintenance, and operational costs, as well as potential savings from reduced material usage and waste. Understanding the long-term economic benefits will help stakeholders justify the investment in sustainable practices.

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# A

## Appendix 1

Can you please start by introducing yourself, (your name, educational background, and professional work experience)?

What motivates you to pursue a career in sustainability (environmental) and what do you find most rewarding in this area?

### **Regarding On-site Assembly and Disassembly Practices**

Can you describe the current practices of on-site assembly and disassembly for prefabricated concrete buildings in your experience?

How do you go about assembly process of prefabricated components? And the same thing for disassembly? How do you make sure that these processes are efficient?

How do these practices align or diverge from the principles of the circular economy?

### **Regarding Recyclable and Reusable Strategies**

Strategies are currently in place for integrating circularity (reuse of building components) in prefabricated concrete construction?

How effective do you find these strategies in minimizing environmental impact?

Can you provide examples of how these strategies have been successfully implemented in projects?

### **Regarding Opportunities and Challenges of Circular Economy Principles**

From your perspective, what are the key opportunities for integrating circular economy principles into prefabricated concrete construction?

What challenges have you encountered in trying to integrate these principles into your projects?

How do you address or overcome these challenges?

In what ways do you think integrating circular economy principles can mitigate greenhouse gas emissions during onsite practices of prefabricated concrete construction?

**General Questions**

What future trends do you anticipate in the field of prefabricated concrete construction, particularly regarding environmental sustainability and circular economy?

How do you imagine the role of prefabricated concrete construction evolving in the context of sustainable development and climate goals for the construction industry?

What steps do you think are necessary for furthering the adoption of circular economy principles in prefabricated concrete construction?

**Final question**

Are there any other thoughts or insights you would like to share related to the environmental sustainability of prefabricated concrete buildings?