Exploring the Opportunities for Reuse in Infrastructure Projects

A Case Study of a Leading Construction Company in Sweden

Master's thesis in Design and Construction Project Management

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Abstract

The construction sector is a significant contributor to resource depletion, greenhouse gas emissions, and construction waste, underscoring the need for more sustainable infrastructure development. This study investigates the feasibility of material reuse in infrastructure by examining its key enablers, barriers, and practical pathways for implementation. A qualitative research design was employed, combining a literature review with a case study of a large-scale infrastructure project in Sweden, augmented by semi-structured interviews with stakeholders. The analysis reveals that integrating reuse considerations into the early design phase is pivotal, reinforced by supporting policies, technical capacity, market readiness, collaborative networks, and cultural acceptance. Notable barriers include the lack of standardized guidelines, inconsistent material quality, and logistical challenges related to storage, transport, and supply-demand coordination. The proposed framework emphasizes early design as the foundation for facilitating reuse, supported by regulatory reform, digital tracking tools, and policy incentives to stimulate adoption. This integrated approach provides a viable route for embedding circular economy practices in infrastructure, with promising environmental and economic benefits for the built environment.

Keywords: Reuse, circular economy, infrastructure projects, sustainable construction, design for reuse, construction waste management, material reuse.

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Gothenburg, August 2025
Hana Dires & Arian Honarkar

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Abbreviations

CE – Circular Economy

CLT – Cross-laminated timber

LCA – life cycle assessment

DTs – Digital Twins

DBB – Design-Bid-Build (Performance contract)

DfD – Design for Disassembly

DfD – Design for Deconstruction

DfR – Design for Reuse

SHM – Structural Health Monitoring

BIM – Building information model

GHG – Global greenhouse gas

WDP – Withdrawn Driven Piles

WHO- World Health Organization

1. Introduction

The construction industry faces significant challenges related to the end-of-life phase of projects, where materials often become waste instead of being repurposed. Reusing construction materials for the same purpose in new projects is crucial for reducing environmental impacts and minimizing the demand for new materials. However, the reuse of construction materials, particularly in infrastructure projects, remains largely overlooked. This chapter emphasizes the vital role of the circular economy (CE), especially the reuse principle within the infrastructure sector of the construction industry. Then, it discusses the identified problem associated with current practices. Finally, the research questions and purpose of the study are presented.

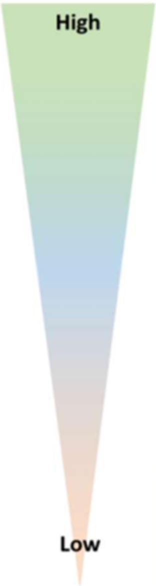
1.1. Background

The construction industry is one of the largest consumers of raw materials globally, significantly contributing to environmental degradation, resource depletion, and waste generation. It accounts for approximately 10% of global greenhouse gas emissions (Thung et al., 2024). Additionally, it is responsible for approximately 36% of the world's energy consumption and nearly 40% of CO2 emissions (Firoozi & Firoozi, 2022). In 2020, 55% of global material demand, equivalent to 59 billion tonnes, was linked to the built environment and infrastructure (Thung et al., 2024). Furthermore, 90 billion tonnes of biomass, fossil energy, metals, and minerals are extracted yearly, with 2.12 billion tonnes of waste discarded. The construction sector is responsible for a substantial portion of this consumption (The World Counts, 2025).

The United Nations Environmental Program highlights that the extraction of natural resources has more than tripled over the past 50 years, primarily driven by the massive construction of infrastructure in many parts of the world and the high material consumption of infrastructure projects. This trend is predicted to increase by 60% by 2060 compared to 2020, indicating the urgent need for a transition toward circularity in the construction sector to minimize raw material demand (Bruyninckx et al., 2024). The construction sector in the EU accounted for over 38.4% of total waste generation in 2022, followed by mining and quarrying at 22.7% (Eurostat, 2023). Europe's infrastructure sector consumes 4.2 billion tonnes of aggregates annually, yet only 7% of these materials are currently part of the circular economy. Increasing this share to 20% could result in estimated savings of approximately EUR 6 billion and 546 million tonnes of aggregates per year (Larsson & Gammelsaeter, 2023).

In Sweden, the construction industry generates approximately 13.6 million tonnes of construction and demolition waste annually, constituting 39% of the country's total waste production (Boverket, 2025). Of this, 0.6 million tonnes are classified as hazardous waste, accounting for 20% of all hazardous waste generated nationally (Boverket, 2025). The construction sector is responsible for about one-fifth of the country's domestic greenhouse gas emissions (Wennesjö et al., 2021). In response to these challenges, Sweden's National Board of Housing, Building, and Planning is actively working to reduce the volume and hazardous nature of construction and demolition waste in alignment with national environmental goals such as a "Good Built Environment" and a "Toxic-Free Environment" (Boverket, 2025). The EU Waste Framework Directive (2008/98/EC) mandates that at least 70% of non-hazardous construction and demolition (C&D) waste be reused or recycled, which has led to an increased focus on material reuse (European Commission, 2020). Despite these challenges, Europe has made progress in recycling construction waste, with around 40% being recycled or reused (Severin & Michaliková, 2024). Sweden has achieved a higher recycling rate, with approximately 55% of non-hazardous C&D waste recycled in 2022 (Boverket, 2025), an environmentally and primarily economically motivated improvement. However, the implementation of reuse practices, especially in infrastructure projects, is still in its early stages and has not received enough attention.

Material reuse is a core principle of the circular economy, as it significantly reduces landfill waste, greenhouse gas emissions, and the demand for virgin materials (Amarasinghe et al., 2024). The circular economy is a system that reduces resource use, waste, emissions, and energy loss by closing or narrowing the material loop (Geissdoerfer et al., 2017). The 10 Rs principle outlines a hierarchy of strategies to improve resource efficiency, reduce waste, and keep material value. As illustrated in Figure 1.1, these principles are ranked from highest to lowest in terms of sustainability impact (Santos et al., 2024). Recycling and recovery are placed at the bottom of the hierarchy due to the higher energy demands required for processing and their greater potential for pollution (Mesa & Esparragoza, 2021).



Reduce	**R1 Refuse**	Do not use it or make a product redundant. For example, is the structure necessary or can you use something existing?
	R2 Rethink	Rethink use. Can it be shared or serve multiple functions. Examples include sharing of equipment between sites and adaptive use.
	R3 Reduce	Use less of it. For example, efficient / optimised design and off-site manufacturing.
Reuse	**R4 Reuse**	Reuse of a product. For example, reuse of windows elsewhere on the site.
	R5 Repair	Repair or maintain, keeping original function. This can be achieved through weatherproofing for example.
	R6 Refurbish	Refurbish, restore or update. A common example in buildings is energy efficient retrofit.
	R7 Remanufacture	Use parts in a new product with the same function, e.g. remanufactured construction equipment.
	R8 Repurpose	Use product or parts in new product with a different function, e.g. structural bricks to decorative internal.
Recycle	**R9 Recycle**	Process materials into something new which can be the same or lower quality, e.g. recycled aggregate.
	R10 Recover	Energy recovery via burning. This includes biomass from the timber construction industry.

Figure 1.1 Circularity hierarchy in the product chain (Source: adapted from Potting et al.,2017 as cited in Santos et al., 2024, with Examples added).

Product repair, refurbishment, repurposing, and remanufacturing are considered reuse operations (Ijomah & Danis, 2012). From a circular economy perspective, reuse is preferred over recycling, as it requires less energy and fewer processing steps to return materials to the construction cycle (Thung et al., 2024). The EU Directive 2008/98/EC defines reuse as any operation where products or components that have not yet become waste are used again for their original purpose, while recycling refers to reprocessing waste materials into new products or materials (European Commission, 2020). Encouraging material reuse not only diverts waste from landfills but also results in substantial economic savings, reduces the need for virgin materials, lowers greenhouse gas emissions, and conserves natural resources (Tam et al., 2018). According to the National Environmental Database, reuse cuts the environmental impact in phases A1 to A3 by about 80% compared to using new materials (Thung et al., 2024). This significant reduction is due to the energy and emissions that are avoided when producing new materials from scratch. Moreover, reusing materials and components extends their lifespan, decreases raw material demand, and mitigates landfill accumulation (Amarasinghe et al., 2024).

Transitioning to a CE is crucial for achieving the United Nations' Agenda 2030 Sustainable Development Goals (SDGs) and the European Green Deal, which targets net-zero emissions by 2050 (European Commission, 2020). CE principles prioritize resource efficiency by minimizing waste and emissions through closed material loops (Geissdoerfer et al., 2017). The EU Circular Economy Action Plan aligns with Sweden's national sustainability targets, fostering long-term environmental resilience (European Commission, 2020).

Infrastructure projects, such as roads, bridges, tunnels, and railways, offer significant opportunities for material reuse. Concrete, one of the most widely used materials in building construction and infrastructure, can be repurposed as aggregate for new construction (Tam et al., 2018). However, this practice is typically not considered a form of reuse. Similarly, steel components from demolished structures can be reused in new infrastructure projects with minimal processing (Kanyilmaz et al., 2023). Despite these benefits, material reuse in infrastructure projects remains limited due to technical, logistical, and regulatory challenges. Addressing these barriers requires governmental support and policy interventions to facilitate the implementation (Ghisellini et al., 2016). This study examines these challenges and opportunities through a case study of a leading construction company in Sweden that is involved in a major infrastructure project. By analyzing real-world practices, the research aims to develop a practical framework that encourages the reuse of materials in infrastructure projects, particularly within the Swedish infrastructure sector. It supports national and EU sustainability goals by promoting resource efficiency and reducing environmental impacts.

1.2. Problem Statement

The construction industry is a major consumer of raw materials and a significant producer of waste, contributing to environmental impact. To reduce this impact, the principles of the circular economy (CE), which focus on material efficiency and waste reduction, have become increasingly important. Specifically, reuse, direct recovery, and reintegration of components without extensive processing can significantly reduce embodied energy, save natural resources, and lower construction costs. CE can be more effectively integrated with industrial ecology to enhance sustainability in construction by encouraging the exchange of materials and by-products across sectors through industrial symbiosis (Deutz et al., 2017; Chertow, 2000). However, despite the reuse aligning closely with these goals, its implementation remains limited.

Research indicates that implementing the CE principle in construction contributes to achieving long-term sustainability targets (Núñez-Cacho, 2018). Using waste materials during different phases of a building's lifecycle can reduce costs and environmental burdens (Akanbi et al., 2019). However, current waste management policies have not sufficiently mitigated the environmental impacts associated with construction waste (Benachio et al., 2020). Moreover, although interest in CE is increasing within the sector (EPA, 2006), the practical implementation of reuse strategies is still hindered by a lack of technical knowledge and operational capacity among professionals (Aljaber et al., 2023).

Current CE efforts in the construction industry mainly focus on recycling and reuse, whereas sectors like manufacturing use more effective strategies, such as remanufacturing and industrial symbiosis (Yang et al., 2022). Even reuse within the construction industry is less compared to recycling, often due to challenges related to regulatory constraints, logistical complexities, and design issues. These challenges are especially pronounced in the infrastructure sector, where research on CE is limited (Akomea-Frimpong et al., 2024; Koźmińska, 2019; Zanni et al., 2018).

Most CE studies focus on buildings, neglecting the unique characteristics of infrastructure projects such as roads, bridges, and tunnels. These projects involve distinct material types (e.g., large-scale concrete, steel), longer service lives, and complex stakeholder coordination, which makes reuse implementation challenging, but offer substantial opportunities for reuse (Akomea-Frimpong et al., 2024). Despite its potential, practical reuse in infrastructure remains rare, with few documented examples to guide industry adoption (Ho et al., 2024). Additionally, data on material flows, component durability, and reuse potential within infrastructure are often scattered or missing (Zanni et al., 2018).

This lack of data, practical guidance, and specific frameworks for infrastructure creates a significant barrier to implementing reuse strategies on a large scale. Therefore, targeted research is needed to explore reuse opportunities, identify obstacles, and suggest solutions designed for infrastructure projects. Enhancing this knowledge is crucial for supporting the shift toward a more circular and sustainable construction industry.

1.3. Research purpose and research questions

The primary purpose of this research is to develop a practical framework to enable the reuse of materials in infrastructure projects. To achieve this, the study addresses the following sub-research questions:

- What are the enablers and barriers for reusing infrastructure materials?
- What logistic strategies are practical for implementing material reuse in infrastructure projects?

1.4. Delimitation

This study is based on the principles of the circular economy, with a specific focus on material reuse. While other circular economy strategies, such as recycling, remanufacturing, or alternative material sourcing, contribute to sustainable infrastructure development, this research focuses on reuse due to its significant climate impact and key role within the 10 Rs framework. As reuse itself is a broad concept within the circular economy, and considering the time constraints of this study, the research is limited to identifying the barriers and enablers of material reuse in infrastructure projects, ultimately aiming to develop a framework that maximizes its implementation.

The study primarily focuses on the leading infrastructure company in Sweden. However, to enhance the depth and reliability of the findings, we also incorporate insights from other stakeholders involved within the project and expertise in the sectors, including Trafikverket, RISE, ReCreat, Leca, and Region Halland, which are active in reuse practices. The literature review primarily uses academic papers and case studies from Sweden and Europe, as the research is conducted within this region. However, in some cases, we also refer to experiences from other countries to broaden the discussion and offer useful comparisons.

Infrastructure is a broad sector that includes railways, roads, dams, bridges, and tunnels. To define the scope of this research clearly, we focus specifically on infrastructure projects while recognizing that material reuse can be applied to various types of infrastructure. The literature review includes examples from different types of projects to build a comprehensive understanding of reuse practices, even if the case focus remains within selected infrastructure initiatives.

1.5. Composition

This thesis is divided into five chapters, which cover an important part of the study. The first chapter provides background information on the topic, explaining the importance of material reuse in infrastructure projects. It outlines the research problem, objectives, research questions, and delimitations of the study. The second chapter consists of a literature review that explores existing research and theories related to material reuse, with a particular focus on the barriers, enablers, and best practices in Sweden and Europe. It also explores relevant frameworks and regulatory perspectives that establish the theoretical foundation for the study. The third chapter describes the research design, data collection methods, sampling techniques, and data analysis procedures used in the study. It details how the research was conducted and explains the chosen methodology. The fourth chapter presents and analyzes the empirical findings, linking to the research objectives. The fifth chapter presents a discussion grounded in the findings from the research and relevant literature reviews. Finally, the sixth chapter concludes the study by summarizing the main research findings, drawing conclusions, and offering recommendations for industry stakeholders. Additionally, chapter six also provides suggestions for future research to support further exploration of material reuse in infrastructure projects.

2. Literature review

This chapter provides an overview of the relevant literature on key concepts related to this research. The main topics include the reuse of material in the construction industry, the enablers and barriers to reuse, and the existing solutions for reuse in the infrastructure sector of the construction industry.

2.1. Circular economy in construction

According to Cheshire (2019), the concept of the circular economy in the construction sector is effectively demonstrated through their model, which is presented in Figure 2.1. This model outlines a sequence of operations that optimize the application of circular economy principles. The innermost circles represent the most time and cost-efficient methods, with "retain" being the most favorable option. The next step involves assessing the possibility of reusing products within the current project and refurbishing materials to meet quality standards. If neither of these options is feasible, explore the possibility of reclaiming or reusing the product in a different context. Remanufacturing should only be considered as a last resort before recycling the product.

The model introduces several key design principles that help integrate a circular economy in the construction industry. The first principle, "building in layers," groups components based on their different lifespans. This approach allows parts with shorter lifespans to be replaced without affecting components intended to last longer. The "Designing-out waste" principle encourages viewing waste as a valuable resource. This approach allows for the reuse of materials that would otherwise be discarded through processes like refurbishing or remanufacturing, thus reducing overall waste. "Design for adaptability" emphasizes the importance of building structures that last longer while ensuring they can be easily modified for different uses over time. This method reduces the need for demolition and construction of new buildings. The "Design for disassembly" principle supports the idea of adaptability. It suggests that when changes are needed, the materials should be designed for easy disassembly. This allows them to be reused in new buildings or projects. The final principle emphasizes choosing suitable materials and promoting those classified as biological or technical. This classification helps identify which materials can be reused, recycled, or returned to nature. Additionally, maintaining a detailed inventory of building components can help find potential markets for salvaged materials (Cheshire, 2019).

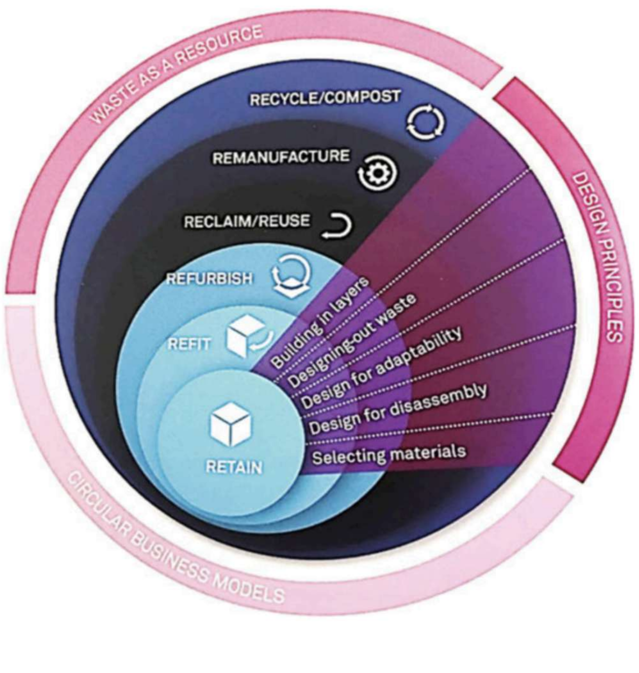


*Figure 2.1 Principles of circular economy within the construction industry (*Cheshire, 2019*)*

A key part of implementing a circular economy is focusing on reuse. It extends the life cycle of construction materials and reduces the need for new resources. Research shows that reuse supports sustainability goals and provides economic advantages by decreasing material costs and lowering waste disposal expenses (Ghisellini et al., 2018). Thus, recognizing how to effectively integrate reuse into construction processes is important for making the most of circular strategies.

2.2. Reuse of material in the construction industry

It is important to distinguish between reuse, recycling, and product transformation in the construction industry. Product transformation means changing products to improve their functionality and quality. Recycling involves processing waste materials to create new ones. In contrast, reuse focuses on extending the lifespan of a material by continuing to use it for its original purpose (Ginga et al., 2020).

Based on the literature, the materials most commonly used in the infrastructure sector are concrete, steel, bitumen, aggregates, polypropylene (PP) drainage pipes, and curbstones. These materials are widely employed in construction projects, particularly in land transportation infrastructure (Mhatre et al., 2021). Concrete and steel are frequently considered traditional construction materials with high carbon and energy intensity (Hildenbrand et al., 2018; Mhatre et al., 2021). They are often the target of substitution efforts aimed at reducing environmental impact. Bitumen, concrete, and steel are specifically highlighted in the context of material circularity in the construction sector (Mhatre et al., 2021). This suggests its significant use in infrastructure projects. As Enges and Katvala (2024) state, the materials used in an infrastructure project can vary significantly. The choice of materials is highly dependent on the nature and type of the project, with concrete, steel, and asphalt being the most significant contributors to climate impact. The following sections will explore different reuse practices to provide a deeper understanding of their implications and challenges.

2.2.1. Reuse of excavated aggregates

Sustainable land management has become a global priority, as shown in recent reports by the United Nations (UN) and the World Health Organization (WHO). These organizations highlight the urgent need for strategies that reduce soil waste and ensure its reuse supports environmental protection and public health (WHO, 2024; UNEP, 2024). In line with this goal, the United Nations Sustainable Development Goal 11 emphasizes that disposing of clean excavated soil in landfills is not a responsible way to handle the environment (United Nations, 2015). Promoting its reuse helps create more sustainable land and waste management systems (UNEP, 2024). The reuse of excavated soil provides several advantages, including shorter transportation distances, lower disposal costs, preservation of landfill space, conservation of natural resources that would otherwise be mined, and reduced environmental and ecological impacts (Walsh et al., 2019). Depending on the intended use, this soil can be repurposed on-site or off-site, provided its properties are suitable for reuse. Critical factors influencing its suitability for reuse potential include geotechnical properties, such as particle size, plasticity, hydraulic conductivity, compressibility, and shear strength, as well as geoenvironmental factors, like pH, total and leachable pollutant concentrations, and organic carbon content (Arulrajah et al., 2013).

In Sweden, several project-driving departments undertake projects involving mass handling; however, there is no structured collaboration on this matter either within or between departments (Johansson & Pelttari, 2023). A major barrier to coordination is the challenge of synchronizing surplus materials from different works in both time and location. This often results in excess materials within individual projects, with the added difficulty of identifying nearby projects that require the same materials within the same timeframe. Nevertheless, Swedish municipalities generally view cross-border collaboration positively and recognize the benefits of participating in a regional mass management plan (Johansson & Pelttari, 2023). They also identify potential advantages in establishing intermediate storage areas, which could support organizational planning and improve coordination between projects both within and across municipal boundaries (Johansson & Pelttari, 2023).

The materials' geotechnical quality and physical composition are crucial for their properties and directly influence the possibilities for reuse. The Swedish Environmental Protection Agency (Naturvårdsverket) categorizes the different types of soil and rock that arise from construction and development projects. The materials are divided into two main categories: construction rock (Type A) and soil and excavated materials (Types B-D), with a decreasing particle size from A being the coarsest.

A. Raw rock and blasted rock
B. Sand and gravel
C. Moraine and soil
D. Clay and silt

Materials from Category D are considered to have more limited reuse potential due to their technical properties, including fine particle sizes and low water permeability. In contrast, materials from Categories A-C can be reused as aggregates after crushing, sorting, or screening (Naturvårdsverket, 2022). Aggregates, a collective term for rock and gravel materials, are essential for construction and civil engineering projects. Without aggregates, developing the infrastructure and buildings that society requires would be impossible. Therefore, construction projects directly influence society's demand for aggregates. Continued high activity and future investments in infrastructure and urban development are expected to increase the demand for aggregate production by approximately 20% by 2040 (Miliute-Plepiene & Sundqvist, 2023). Previously, natural gravel was the primary source of aggregates. However, crushed rock has largely replaced it due to its classification as a finite resource and its important role in the country's water supply. Over the past 30 years, the use of natural gravel in aggregate production has decreased from 77% to 8%, while crushed rock accounted for 91% of the total aggregate deliveries in 2020 in Sweden (SGU, 2021b). Many of today's aggregates also come from construction rock generated during building and civil engineering projects (Miliute-Plepiene & Sundqvist, 2023).

2.2.2. Reuse of concrete and masonry

Concrete recycling has been extensively researched and widely practiced within the construction industry. However, the direct reuse of concrete, where material in its original form for new constructions remains relatively rare and not widely adopted. Concrete is the most accessible recycling building material. However, reuse is more challenging due to the cost sensitivity of transport distance (Schützenhofer et al., 2022). European countries seem ahead in integrating reuse, where a reclamation-led approach to demolition and reversible design strategies has been researched in recent years. The European Union has even issued the Waste Framework Directive, which aims to reuse instead of recycling (Union, E. 2008).

Projects incorporating reused concrete have primarily utilized it for non-structural applications, such as concrete tiles, paving, and curbs. In cases where it has been used structurally, applications have been limited, for example, the reuse of prefabricated housing panels in Finland (Huuhka et al., 2015).

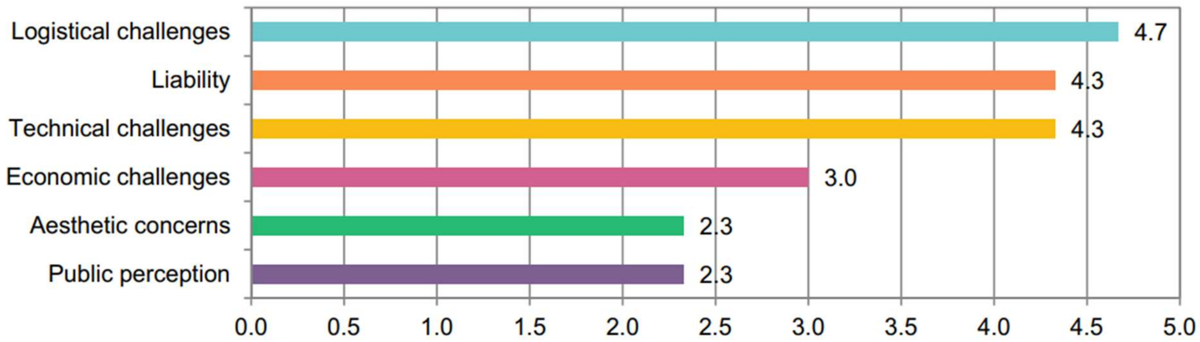


Figure 2.2 Ranking of obstacles to concrete reuse (Al-Faesly & Noël 2021).

Recent research(see Figure 2.2) has identified several key barriers to reusing concrete in construction. This is based on feedback from various stakeholders in the Canadian concrete industry. According to Al-Faesly and Noël (2021), the biggest challenge mentioned by participants was logistical issues related to handling, storing, and transporting reused components. Liability concerns and technical difficulties, such as differences in material properties and contamination risks, were also highlighted. Some respondents noted the lack of formal design standards and guidelines as a source of uncertainty, especially for structural applications, but this was not seen as the top barrier. Economic factors, like the cost of processing and transporting reused concrete compared to getting new materials, further hinder widespread use. Additionally, limited awareness and practical experience among construction professionals show the need for better education and demonstration projects. Overall, these challenges suggest that technical, legal, and logistical barriers are more pressing than informational or institutional challenges. This highlights the importance of focused policy support and industry knowledge-sharing to encourage greater use of concrete reuse. (Al-Faesly & Noël, 2021).

Concrete, which plays a major role in the infrastructure sector, has various ways to be reused. Sometimes, it is possible to reuse elements directly, like precast panels or bricks (Habert et al., 2020). However, this strategy requires careful assessment of the existing element's condition and suitability for the new application. Downcycling involves reclaimed concrete and masonry for lower-grade applications, such as fill material or landscaping (Brunner & Rechberger, 2016). While this approach may not offer the same environmental benefits as higher-value reuse, it diverts material from landfills. Moreover, reclaimed concrete and masonry can be used as raw materials to manufacture new products, such as paving stones, blocks, or even cement (Behera et al., 2014). The quality of these recycled aggregates can vary depending on the source material and processing techniques (Neville, 2011).

However, concrete recycling, primarily for use as aggregates, is a well-researched area, and the direct reuse of concrete elements in infrastructure remains a relatively under-explored topic. However, some studies address using recycled concrete aggregates in pavements and other infrastructure applications (Agrawal et al., 2020). There is a lack of literature and comprehensive investigations into the feasibility and benefits of directly reusing concrete components, such as bridge beams, concrete pipes, maintenance holes, and concrete blocks for pavement within infrastructure projects.

Reusing concrete piles in construction offers economic and environmental benefits by extending the service life of structural elements and reducing the need for new materials. Unlike recycling, which involves crushing concrete for use as aggregate, reuse retains the structural integrity of the pile for direct application in new projects (Cui et al., 2020). Technological improvements in pile extraction, inspection, and refurbishment have made it easier to assess structural integrity and modify piles for different ground conditions (Wang et al., 2024). Researchers have also examined methods for evaluating the durability and bearing capacity of WDP (concrete piles), as well as the performance of WDP and its applicability (Cui et al., 2020).

2.2.3. Reuse of steel

Steel is essential for building infrastructure and improving living standards. As the population continues to grow and cities expand, the steel demand is expected to increase (Jernkontoret, 2020). Directly reusing steel components is essential for minimizing environmental impact (Öhman et al., 2021). The iron and steel sector accounts for approximately 7% of annual global greenhouse gas (GHG) emissions, making it a significant focus for sustainability efforts (HYBRIT, n.d.; Kanyilmaz et al., 2023). In Sweden, the industrial sector is responsible for nearly one-third of total national emissions, with the steel sector alone contributing 10% (MIT Climate Portal, 2024; Kanyilmaz et al., 2023). This shows the urgent need for sustainable solutions and strategies to improve steel reuse in infrastructure projects. Steel is produced by combining iron with carbon and recycled steel, creating a material up to 1,000 times stronger than pure iron (Öhman et al., 2022). This shows how important it is to manage waste and recover materials efficiently to make the most of steel components. The reuse and recycling of steel by-products in construction are vital for sustainability. This makes improvements in technology and changes in policy necessary for increasing the efficiency of steel reuse (Colla et al., 2023).

Several real-world examples show the practicality and advantages of reusing steel. A study by Alper Kanyilmaz et al. (2023) details two notable cases. The first case involves a centuries-old bridge in the Yorkshire Dales (Figure 2.3). This bridge was condemned and replaced with a new deck made from reused steel sections, which saved 8 tons of carbon dioxide. This project highlights that steel reuse is viable in large-scale developments and smaller, practical applications. The second case is the Port of Dundee East Redevelopment (Figure 2.4), which repurposes a surplus gas pipeline to fabricate 1,070 tons of steel tubes for piling. Using reused steel instead of newly manufactured materials led to 95% to 97% of carbon savings, totaling a reduction of 2,185 tons of carbon (Kanyilmaz et al., 2023). These cases demonstrate that reused steel can meet high engineering standards while significantly reducing carbon emissions and costs.

Figure 2.3 East Arkengarthdale Bridge project (Source: Cleveland steel & Tubes Limited; Kanyilmaz et al., 2023)

Figure 2.4 Port of Dundee East Redevelopment (Source: Cleveland Steel & Tubes Limited; Kanyilmaz et al., 2023)

Direct reuse of structural elements, such as beams, columns, or other components, means using them in their original form or with minimal changes (Yellishetty et al., 2011). This method has the most potential for reducing processing and keeping embodied carbon intact. However, like with concrete, it is important to carefully check the condition of the existing element and its fitness for reuse. Re-fabrication involves cutting and re-welding reclaimed steel into new shapes and sizes for different uses (Hasanbeigi et al., 2014). This provides more flexibility with reclaimed steel, including pieces that have minor defects or damage. Steel or metal cladding panels and roofing sheets can often be reused with little processing, which offers both environmental and aesthetic benefits. Better inspection techniques, such as non-destructive testing methods, help assess the condition and properties of reclaimed steel more accurately (Yellishetty et al., 2011). Similarly, improvements in cutting and welding technologies can help reshape reclaimed steel into new forms. Additionally, creating clear grading systems and quality control measures for reclaimed steel is vital for building trust among users and encouraging more widespread use. There is a gap in the current knowledge. We need to establish better and more consistent guidelines for reusing steel. This involves addressing issues such as quality control, market development, and support from policies (Crowther, 2018).

2.2.4. Reuse of other components

Several approaches to wood and timber reuse with distinct characteristics exist in the current literature. First, direct reuse, which involves using timber elements in their original form or with minimal modification, including reusing structural elements, offers the most significant potential for minimizing processing and maximizing embodied carbon retention (Sandin et al., 2022). Re-milling and remanufacturing, on the other hand, involve processing reclaimed timber into smaller dimensions or different forms. Re-milling and remanufacturing involve processing reclaimed timber into smaller sizes or different shapes. Re-milling includes planning, sanding, and re-profiling timber to make new products like flooring, paneling, or furniture. Remanufacturing goes further by adding processes like finger-jointing or laminating to create engineered wood products such as glulam or CLT (Dutil et al., 2015). This method allows for more flexible use of reclaimed timber, even pieces that have small defects or damage (Aicher et al., 2014).

In addition, cascading use refers to utilizing reclaimed timber for lower-grade applications over time. For example, high-quality timber from a demolished project might be reused in a new project for structural purposes. Conversely, lower-grade timber from the same source can serve non-structural roles, such as in furniture or landscaping (Nussbaumer et al., 2018). This approach makes the most of reclaimed timber while cutting down on waste. Lastly, reusing and upcycling focus on the artistic and innovative uses of reclaimed timber. This usually requires minimal processing and highlights the unique character and history of the wood. We see this in furniture design, art installations, and decorative features in buildings (Addington et al., 2012). This method adds value to reclaimed timber and raises awareness about the possibilities of material reuse.

Effective wood reuse strategies often integrate multiple approaches and are guided by the abovementioned principles (Ottenhaus et al., 2023). For example, a project might involve directly reusing some timber elements, re-milling and remanufacturing others, and cascading use for different applications (Nussbaumer et al., 2018). This integrated approach allows for maximizing the utilization of reclaimed timber and minimizing waste. The entire process can be guided by Design for Disassembly (DfD) principles, which aim to facilitate future reuse by designing buildings for easy deconstruction (Crowther, 2018). Furthermore, Life Cycle Assessment (LCA) can evaluate the environmental impacts of different reuse strategies, providing a basis for informed decision-making (ISO 14040, 2006).

While studies have looked at timber reuse in buildings (Ottenhaus et al., 2023; Nussbaumer et al., 2018), they have not focused much on the specific challenges and opportunities in infrastructure projects. This lack of research is worrying because infrastructure development requires a lot of materials, and wood reuse could offer significant environmental advantages in this area (Santos et al., 2024). The unique performance needs, often larger size, and longer lifespans of infrastructure projects, along with complex logistics, require careful study to understand how to make wood reuse feasible and to improve strategies for its use in structures like bridges, retaining walls, or temporary works.

Lightweight expanded clay aggregate is a promising material for reuse in infrastructure projects because it is durable, light, and has great insulating properties. It is made by heating natural clay at high temperatures. LECA is often used in road construction, railway embankments, and drainage systems. It helps reduce weight and improve stability in weak soils (Rashad, 2018). Recently, the reuse of lightweight expanded clay has gained significant attention because of its environmental advantages and applications in various industries. LECA is a porous material created by heating clay at high temperatures. It is commonly used in construction, horticulture, and insulation (Leca Sverige AB, 2023). Reusing LECA means collecting and repurposing material from construction waste or discarded products. This approach helps decrease the demand for new raw materials and reduces waste (Uceda-Rodríguez et al., 2022). The lightweight and durable properties of this material make it ideal for applications such as structural aggregates and drainage systems. It also provides an eco-friendly choice for soil amendments (De Brito et al., 2019).

2.3. Reuse enablers

Reuse enablers in infrastructure are the policies, technologies, and design methods that make it easier to repurpose materials, buildings, and structures. Reuse in infrastructure often highlights environmental benefits, economic viability, and regulatory issues. This review looks at different viewpoints on reuse enablers, based on research and various studies.

2.3.1. Policy and regulatory support

Government policies and regulations play a key role in encouraging material reuse by creating rules and incentives. Swedish and EU policies back circular economy ideas, creating a favorable regulatory environment (Gerhardsson et al., 2020). The EU Circular Economy Action Plan seeks to cut waste while boosting reuse and recycling in the construction industry (European Commission, 2020). Sweden has made strides with initiatives like the Swedish Environmental Code and the National Waste Management Plan, which support sustainable construction (Boverket, 2025). Strengthening regulatory frameworks is vital for promoting circular construction. These frameworks provide clear guidelines and standards for reusing materials in infrastructure projects. They help ensure safety, quality, and environmental sustainability (Santos et al., 2024).

Regulatory changes and governmental measures, such as the EU Waste Framework Directive (WFD) and the Resource Efficiency in the Building Sector Report, aim to improve material efficiency and promote sustainability in the Architecture, Engineering, and Construction (AEC) industry. These policies encourage stakeholders to prioritize reused and recycled materials by setting clear guidelines and compliance requirements. This approach follows the principles of a circular economy and reduces the environmental impact of construction activities (Schützenhofer et al., 2022). Similarly, Norwegian government policies are recognized as strong drivers of sustainability and circular economy practices. By offering incentives, funding, and regulatory frameworks, these policies encourage businesses to adopt material reuse strategies (Kummen et al., 2023). Aligning government actions with business operations is essential for a seamless transition to a circular economy in the construction sector. The Swedish Environmental Protection Agency (EPA) highlighted in its 2023 report, In-depth Evaluation of the Swedish Environmental Objectives, the need to transition to a resource-efficient and non-toxic society (Swedish Climate Policy Council, 2024). This transition focuses on optimizing resource use within circular flows while conserving energy, primary materials, land, and water.

2.3.2. Technological advancements and digitalization

Technological innovations have become strong supporters of material reuse in infrastructure. Using digital technologies is vital for carrying out circular strategies at different stages of a building's life. One of these technologies, Digital Twins (DTs), has gained popularity in civil engineering, especially for Structural Health Monitoring (SHM) of large-scale projects. These virtual models of physical assets allow for real-time monitoring, predictive maintenance, and informed decision-making throughout the life cycle of an infrastructure project (Sakr et al., 2024).

In addition to DTs, tools like Building Information Modeling (BIM), Material Passports (MPs), and digital marketplaces have greatly improved how we track, assess, and reuse materials (Çetin et al., 2021). BIM is becoming more common in managing infrastructure assets. It offers a clear digital view of a facility's physical and functional traits. This includes creating BIM models for roads, rails, bridges, tunnels, and more. Bridges, in particular, present challenges for digitalization because of their complex shapes. However, recent progress in 3D surveying and artificial intelligence has allowed for the automated creation of accurate BIM models (Rade Hajdin et al., 2023). This digitalization process boosts the potential for reusing materials by giving detailed information about existing structures.

Additionally, BIM supports circularity assessments and the generation of end-of-life models, further supporting material recovery and reuse efforts (Charef & Emmitt, 2020). Integrating BIM with material tracking systems improves planning, documentation, and resource management throughout a building's lifecycle (Gerhardsson et al., 2020) while facilitating design for disassembly. This approach improves material recoverability in future deconstruction projects (Knoth et al., 2022).

Material Passports (MPs) provide essential data on material composition, lifespan, and reuse potential, simplifying the identification of reusable components in construction projects (Santos et al., 2024). Additionally, artificial intelligence (AI) and scanning technologies enable automated material assessments, ensuring that materials from deconstructed buildings meet safety and quality standards for Reuse (Çetin et al., 2022). AI inspection systems enhance digital twin (DT) capabilities by detecting anomalies, identifying hazardous materials, and assessing the physical condition of building elements (Çetin et al., 2022). AI techniques help with infrastructure material characterization at different scales. They extract failure-related information from images and point clouds, evaluate performance from sensor signals, and predict long-term performance using big data analytics (Hou et al., 2023). These abilities improve the potential for material reuse by assessing structural conditions and optimizing maintenance strategies. Additionally, scanning technologies like point cloud scanners and drones create accurate digital representations of buildings, combining interior and exterior models to assist with maintenance and renovation efforts (Çetin et al., 2022).

Drones are increasingly used to monitor construction projects. They provide early warning capabilities, situational assessments, and decision support, including structural fault detection and security threat identification (Flammini et al., 2016). This technology enables more frequent and comprehensive inspections, potentially identifying reuse opportunities. Another key technology in infrastructure assessment is Ground Penetrating Radar (GPR), a widely used non-destructive testing (NDT) technique for bridges, which provides efficient assessments of structural conditions, making it a valuable tool for evaluating reuse potential (Boldrin et al., 2024). This skill to carry out non-destructive assessments is crucial for figuring out if we can repurpose existing structures. It helps to maintain safety and prolong the lifespan of infrastructure parts.

2.3.3. Environmental and Economic Benefits

Reusing materials in infrastructure projects provides important environmental and economic benefits. It supports the circular economy and sustainable development. From an environmental standpoint, reusing materials can greatly decrease carbon emissions and waste. For example, reusing steel beams can cut CO_2 emissions by as much as 77% (Kim & Kim, 2020). This shows that material reuse is a key strategy for improving sustainability and lowering greenhouse gas emissions in construction. Also, salvaging and reusing building materials from old structures is vital for sustainable construction and environmental protection. It helps reduce construction and demolition waste in landfills while preserving natural resources (Ungureanu et al., 2024).

However, the economic benefits of reuse are not always straightforward. While some studies indicate that substantial economic and environmental savings can be achieved simultaneously (Laefer & Manke, 2008), others suggest that the cost of processing reusable materials, such as reused steel beams, can increase overall project expenses by up to 40% (Kim & Kim, 2020). The economic viability of reuse often depends on factors such as project size, material availability, and processing requirements. For instance, a Cost-Benefit Analysis (CBA) of a water reuse project in Italy revealed that environmental benefits often need to be factored in to make the project economically viable (Arena et al., 2020). Despite these challenges, reclaimed materials can lower material costs and get rid of landfill disposal fees for construction waste. Investing in circular practices results in long-term savings for construction companies by cutting down on material expenses and waste disposal costs (Gerhardsson et al., 2020). Furthermore, the material recovery and reuse sector can create jobs, which strengthens the economy (Gerhardsson et al., 2020). Circular economy (CE) innovations, including material recovery and reuse, are associated with higher turnover and job growth (Horbach & Rammer, 2019).

The construction sector can significantly lower greenhouse gas emissions by minimizing waste and promoting reuse, aligning with global sustainability goals and climate change mitigation efforts (Gerhardsson et al., 2020). For instance, managing 1,800 tonnes of reusable office materials annually could result in climate savings of approximately 3,300 tonnes of CO_2 equivalents per year, equivalent to around 1,300 round-trip flights between Gothenburg and Thailand (Wennesjö et al., 2021). This highlights the important climate impact of reusing and recycling materials in construction projects. The environmental benefits of reusing materials in infrastructure projects are usually clear, but the economic advantages can differ. To make the most of reuse as both an economic and environmental support, it's crucial to look at the entire life cycle of materials, create efficient reuse systems, and put in place policies that encourage reuse practices (Knoth et al., 2022). As the construction industry moves toward a more circular economy, the connections between economic and environmental benefits are expected to grow. This makes material reuse a more viable strategy for sustainable development.

2.3.4. Stakeholder Collaboration

Stakeholder collaboration is key to successfully reusing materials in infrastructure projects. It helps tackle challenges and increases the benefits of circular economy principles. Practical cooperation among different actors in the value chain is essential for improving reuse practices (Knoth et al., 2022). Strong communication and teamwork between manufacturers, architects, contractors, environmental consultants, and public institutions can greatly improve the implementation of reuse strategies (Knoth et al., 2022). Moreover, multi-stakeholder platforms and citizen engagement are vital in supporting adaptive reuse. Participatory approaches contribute to better decision-making and more effective policy development (Ikiz Kaya et al., 2021). In the construction industry, coordinated efforts among contractors, suppliers, regulatory bodies, and research institutions are key to maximizing the impact of sustainable practices and accelerating the transition toward more sustainable underground construction (Sharghi & Jeong, 2024). Similarly, effective partnerships between contractors, material suppliers, local governments, and other relevant stakeholders can significantly improve the feasibility and success of reuse initiatives (Ikiz Kaya et al., 2021).

Moreover, collaboration among businesses, governments, and research institutions is critical for implementing innovative material recovery and reuse concepts. Industry associations and research partnerships contribute to improved waste management practices and promote material reuse within the architecture, engineering, and construction (AEC) sector (Schützenhofer et al., 2022). Strong collaboration among stakeholders and a comprehensive approach to reuse are crucial for overcoming obstacles and enabling the shift to a circular economy in the construction industry (Kummen et al., 2023). This cooperation helps connect goals and supports the transition from linear to circular systems. Furthermore, working together is essential for reuse in infrastructure projects. It addresses challenges, brings together different interests, and encourages innovative solutions. By promoting transparency, involvement, and joint decision-making, stakeholders can collaborate to tackle barriers and enhance the environmental and economic benefits of reuse practices in construction and infrastructure development (Karaca et al., 2024).

2.4. Different perspectives on barriers of reuse

The construction industry is often characterized by a conservative approach that favors linear processes over circular ones (Knoth et al., 2022; Ericsson et al., 2024). Various studies indicate that this preference stems from a gap in education and knowledge among professionals regarding circular economy principles, which hinders the adoption of sustainable practices (Firoozi & Firoozi, 2022; Kummen et al., 2023; Gerhardsson et al., 2020). Many organizations depend on outdated project management practices that do not support the complexities of reuse. These old methods hinder effective communication, collaboration, and decision-making, which are essential for integrating reused materials into construction projects (Ericsson et al., 2024). The need to improve strategies and coordination across the value chain is crucial for overcoming challenges. However, even with its environmental and economic benefits, putting reuse strategies into practice in infrastructure remains limited due to various obstacles. These obstacles can be grouped into three main areas: financial, quality, and logistical.

2.4.1. Financial Perspective

Economic and financial factors play a significant role in hindering the adoption of circular practices in construction. The initial costs of implementing circular methods are often higher than traditional construction techniques (Firoozi & Firoozi, 2022). Several studies have found that economic and market-related obstacles significantly hinder material reuse practices (Aljaber et al., 2023; Lobo et al., 2021). One major financial challenge is the high upfront investment needed to adopt circular economy strategies in construction (Aljaber et al., 2023). This initial financial burden can make companies hesitant to embrace reuse practices, especially when the long-term benefits are not immediately clear.

Additionally, the lack of economic incentives and a poorly developed market for reusing construction materials slows down adoption (Sigrid Nordby, 2019). Weak demand for reused materials leads to limited supply, creating a cycle that weakens the financial viability of reuse efforts. High implementation costs pose a big challenge, but waste reduction through reuse can also provide potential cost savings (Karaca et al., 2024). This situation shows the complexity of financial issues in material reuse. Short-term costs need to be balanced with long-term savings and environmental benefits.

Studies indicate that reuse is often more labor-intensive and costly than conventional construction methods (Rakhshan et al., 2020). Incorporating Design for Deconstruction (DfD) can streamline reuse by considering flexibility and material traceability early in the project (Eberhardt et al., 2019). However, designing with reused materials adds complexity, as architects must source materials that fit the project, manage uncertainties in specifications, and account for storage costs. The need for flexible designs and early material claims adds to inventory costs (Gorgolewski et al., 2008). The lack of a well-established market for reused materials also drives up costs (Chinda & Ammarapala, 2016). Although digital trading platforms are emerging, demand is still low (Caldera et al., 2020). Financial incentives, such as higher taxes on landfills and new products, could encourage circular construction by promoting the resale of materials rather than disposal. This would help the market grow (Chen et al., 2022).

The financial impact of reusing materials can be unpredictable. Stakeholders might worry that the costs of sourcing, transporting, and processing reused materials could exceed those of new products. This concern can make them reluctant to embrace reuse practices (Kummen et al., 2023). Reuse often involves higher costs due to transportation, storage, and reconditioning. This can make it less appealing than new materials, particularly without clear economic incentives (Ericsson et al., 2024). To tackle these financial challenges, we need to create financial incentives (Aljaber et al., 2023) and clarify or adjust regulations around the trading and use of reused construction products (Sigrid Nordby, 2019). These steps will be crucial in promoting circular construction practices. These measures will be essential in advancing circular construction practices.

2.4.2. Quality Perspective

Reusing materials in construction poses various quality-related challenges. Designers and construction companies find it hard to identify suitable reclaimed structural components that meet quality standards (Gorgolewski, 2006) because there are no standardized methods for assessing reuse impacts. This lack of standards makes it tough for companies to adopt reclaimed materials widely (Nyhlin & Åfreds, 2022). Additionally, without a system for exchanging reclaimed components, sourcing high-quality reused materials during a project's life cycle becomes difficult (Gorgolewski, 2006). There are also technical risks; materials may have been exposed to harmful substances like asbestos, leading to safety and health problems (Rameezdeen et al., 2016). The service life of construction materials is crucial for their potential reuse. Materials with longer lifespans are easier to repurpose effectively. Well-maintained and durable materials can go through multiple use cycles, which cuts down on the need for new resource extraction and reduces environmental impact (Durmisevic & Brouwer, 2002). Moreover, environmental exposure, wear and tear, and chemical reactions can weaken materials, making them less suitable for reuse without significant repair or treatment (Tingley & Davison, 2011).

Regulatory barriers hinder reuse, as existing building codes are not fully adapted to reused materials (Huang et al., 2021). Most regulations and policies are designed for conventional construction models, often failing to support circular practices or environmental incentives (Firoozi & Firoozi, 2022). While Sweden has a national strategy for sustainable construction that integrates life cycle analysis into building regulations, it places minimal emphasis on deconstruction, limiting its impact on reuse initiatives (Firoozi & Firoozi, 2022). Additionally, there are unclear design rules and standards for reused elements (Kanyilmaz et al., 2023). This creates uncertainty about the quality and safety of reused materials, which makes stakeholders hesitant to use them in new projects. Another major challenge is getting reliable information about reused construction products. The limited availability of accurate and sufficient data in digital form for describing and evaluating recovered materials makes the reuse process more complicated (Byers et al., 2024). Furthermore, the absence of technical control and certification procedures for reused materials raises quality concerns (Sigrid Nordby, 2019). This could make reuse less attractive for large-scale adoption.

Contractors are often opposed to engaging in construction projects that mandate material reuse and recycling due to the added complexity and time required to meet these requirements (Wennesjö et al., 2021). The increased workload and logistical difficulties associated with sourcing and validating reused materials can discourage stakeholders from embracing circular practices (Firoozi & Firoozi, 2022). Additionally, infrastructure projects involving large quantities of materials such as soil, stone, and gravel face further challenges as public awareness and understanding of material management remain limited (Larsson & Gammelsaeter, n.d.). This limitation could hinder material handling and reduce quality.

Mandatory certifications and regulatory adjustments can address existing challenges (Chen et al., 2022). Furthermore, prefabrication and industrialized building systems (IBS) provide better quality control, less waste, and more opportunities for reuse and recycling compared to traditional construction methods (Begum et al., 2010). However, using these construction techniques also comes with challenges. These include higher initial costs, a lack of expertise, and difficulties in connecting components (Sun et al., 2020).

2.4.3. Logistical Perspective

Logistics involves the movement of materials from the origin to the consumer. It is defined as the strategic management of procurement, movement, storage of materials, parts, inventory, and related information flows (Christopher, 2022). The construction industry faces criticism for being inefficient and underperforming. This is largely due to its fragmented nature, where each project is organized differently and the design and construction phases are separate. This fragmentation causes logistics issues because of poor communication and the transfer of information. Studies indicate that 40% of deliveries have problems related to timing, quantity, location, or damage.

Moreover, the industry has been slow to embrace technologies that could improve logistics processes (Dubois et al., 2019). Reuse presents its challenges, especially in reverse logistics, which means retrieving, refurbishing, and redistributing used materials (Ding et al., 2023). While reverse logistics is common in manufacturing, its application in construction is still limited (Hosseini et al., 2015). Poor coordination, unpredictable supply chains, and slow technological adoption hinder its implementation. These challenges require improved tracking systems, material documentation, and strategic stakeholder collaboration.

Construction projects often work under tight timelines. This pressure can lead to a preference for quick solutions rather than the longer processes involved in reusing materials (Kummen et al., 2023). As a result, stakeholders might favor new materials, seeing reuse as an extra challenge. Many municipalities also lack the necessary planning and infrastructure to handle the storage, transportation, and distribution of reused materials. This situation complicates the reuse process even more (Kummen et al., 2023). Limited information sharing, cooperation, and coordination among supply chain participants further slow down reuse efforts. This lack of teamwork reduces confidence in the quality and performance of construction and demolition waste (CDW)-related materials. Consequently, it lowers their demand and usage (Pimentel et al., 2022). Additionally, poor management and recycling systems for CDW, along with the lack of established markets for reused materials, create inefficiencies in processing and distribution (Pimentel et al., 2022). The lack of proper facilities and market structures significantly hampers the adoption of reused materials in infrastructure projects. Logistical challenges are compounded by extra transportation stages, such as moving materials to and from temporary storage locations or facilities where they are tested or treated before being brought back to the site for reuse. This leads to increased direct costs for transport and loading, as well as indirect costs like greenhouse gas emissions, which can negatively impact the environment and finances (Gomes Correia et al., 2016).

Another major challenge in construction logistics is the potential loss of productivity from on-site delays and disruptions. These issues often arise from conflicts between workforce schedules, material availability, and equipment coordination (Magill et al., 2020). This highlights the need for better logistical efficiency to ensure smooth transport of all materials from the point of manufacture or recovery to their final use on construction sites. Using 4D Building Information Modeling (BIM) in logistics planning can offer valuable insights, optimize material flows, and improve the efficiency of reused materials (Magill et al., 2020).

2.5. Existing solutions for reusing in infrastructure

Reusing materials in the construction industry depends on effective logistics solutions for circular material flows. One common method is reusing materials on the same construction site. Here, workers take materials apart, store them, and put them back together without leaving the site. This method lowers transportation costs and emissions while making sure that resources are used efficiently.

Another method involves moving materials to an external storage facility before bringing them back to the project. While this allows for better organization and quality control, it also requires additional logistics planning and storage space. Beyond individual projects, reuse can be managed across multiple construction sites within the same organization. This ensures that surplus materials from one project are effectively used in another. This approach needs efficient inventory management and coordination to match available materials with demand. The most complex solution involves inter-organizational reuse, where materials circulate between companies, industries, or private users through digital and physical marketplaces. While this method offers the most tremendous potential for large-scale reuse, it also introduces challenges related to supply chain integration, legal ownership, and material certification. Overcoming these barriers requires improved traceability systems, standardized processes, and collaborative networks within the construction sector (Bosch et al., 2023).

Moreover, the reuse of naturally excavated materials has historically been practiced at some level. However, reclaiming building components from demolition is often hindered by logistical challenges and the perception that new materials are more cost-effective than the labor-intensive reuse process (Rose & Stegemann, 2018). While environmental concerns are important, quality and price mainly influence consumer demand for construction materials (Czarnecki & Rudner, 2023). Thus, materials made from waste must show great performance to gain market acceptance. This highlights the ongoing challenge of balancing sustainability and quality in reusing construction materials.

Design for Reuse (DfR) is an approach that integrates reclaimed components into the design of new structures (Iacovidou & Purnell, 2016; Kim & Kim, 2020). It optimizes the use of existing materials by preparing them for efficient incorporation into new projects, which may include dismantling, cleaning, testing, storage, and re-fabrication. Successful DfR requires design flexibility, particularly when new layouts differ from the original, and close collaboration between designers, engineers, and constructors to optimize results (Iacovidou & Purnell, 2016). Studies confirm that DfR reduces structural environmental impact through reclaimed materials (Kim & Kim, 2020).

Moreover, Design for Deconstruction (DfD) aims to close construction component loops by enabling the economic recovery of structural components at the end of their lifecycle. This approach focuses on designing for easy disassembly and reuse. It reduces the need for raw materials and lowers environmental impact by limiting reprocessing (Iacovidou & Purnell, 2016). To support the adoption of DfR and DfD strategies, specialized education and training for construction professionals are crucial. These initiatives close the skills gap in the industry and promote sustainable construction practices. Supportive policies and market opportunities can further strengthen these efforts (Iacovidou & Purnell, 2016).

A material bank is a centralized database that keeps detailed information on reusable materials. This includes type, quantity, condition, and properties. This system allows for quick assessments and informed reuse decisions. It also encourages collaboration among stakeholders like designers, builders, and project managers by providing shared access to reusable materials. The material bank also streamlines decision-making by optimizing material procurement planning and suggesting efficient cutting and procurement strategies to minimize waste (Kim & Kim, 2020). Besides, it facilitates economic and environmental impact assessments (e.g., LCA and LCCA), enabling stakeholders to evaluate the benefits and drawbacks of reusable materials and make sustainable choices (Kim & Kim, 2020). By integrating BIM data, the material bank further enhances material management by providing detailed attribute information to identify and track reusable building components efficiently.

The reuse of aggregates from excavation and demolition activities is an increasingly common practice in sustainable infrastructure development. In Sweden, guidelines such as those found in AMA Anläggning encourage the reuse of excavated material, often referred to as "Fall A" solutions, provided that the material meets specified geotechnical and environmental standards. This practice reduces the need for virgin aggregate extraction, lowers transport emissions, and minimizes landfill use. Common solutions include on-site screening and quality control to assess particle size distribution and contamination levels, allowing suitable material to be repurposed for backfilling, sub-base layers, or temporary road surfaces. Public infrastructure projects, especially those commissioned by municipalities or Trafikverket, often include reused aggregates to improve their environmental impact and reduce costs. There is a growing use of digital material tracking systems to ensure traceability and compliance. However, challenges persist in maintaining consistent quality and obtaining regulatory approvals, particularly in urban areas with greater contamination risks (Andersson et al., 2020).

3. Methodology

The research methodology chosen to meet the study's goals and answer the research questions included a literature review, an interview, and a case study. The primary purpose of this research is to develop a practical framework to enable the reuse of materials in infrastructure projects. A qualitative research approach was considered the best fit. This method offers a deeper understanding of industry practices, views, and challenges related to material reuse in infrastructure.

This chapter details how the study was conducted, covering the research approach, data collection methods, and ethical considerations. It also reflects on the chosen methodology, discussing its strengths, limitations, and relevance to the research focus. Including a case study improves the study by offering practical insights and real-world examples, which help demonstrate how material reuse is used in actual infrastructure projects.

3.1. Research Philosophy and Approach

This study is based on a research philosophy that influences how knowledge is understood and built. These ideas will guide our research strategy and the methods we select as part of that strategy. Two important aspects, ontology and epistemology, form the basis of this philosophical approach (Saunders et al., 2009). Ontology, which looks at the nature of reality, is viewed through a social constructivist lens. This perspective suggests that reality is not objective and fixed; rather, it is shaped by social interactions and contextual experiences. In this study, stakeholders like project managers, environmental experts, and suppliers see and interpret the idea of material reuse in infrastructure in different ways. This ontological perspective supports the idea that these various viewpoints are all valid and important for understanding how reuse is handled in practice. On the epistemological side, the study takes an interpretive approach, highlighting the significance of personal meaning and understanding. Knowledge is built by interpreting participants' experiences, insights, and contextual narratives. This is operationalized through semi-structured interviews, which allow for an in-depth exploration of personal and professional experiences related to reuse practices. The study also employs an abductive approach, which allows for an iterative movement between theory and empirical data. Rather than strictly applying existing theories (deductive) or generating a theory solely from data (inductive), the abductive approach facilitates the discovery of new insights by moving back and forth between empirical observations and conceptual frameworks. This flexibility enabled the identification of emerging themes, such as barriers, enablers, and strategic opportunities for material reuse, based on the lived experiences of professionals in the field.

3.2. Research design and the research process

This research is based on a theoretical framework established through a comprehensive review of scientific literature, including academic articles, journals, and reports. The literature search utilized databases like Google Scholar, Chalmers Library, ResearchGate, and Scopus, with keywords such as "infrastructure and reuse," "construction logistics and reuse material," "barriers to infrastructure reuse material," "enablers of infrastructure reuse material," "construction materials and reuse," "reuse material," and "steel" to identify relevant sources. This literature review provided essential insights into the challenges, opportunities, and frameworks related to infrastructure material reuse, particularly within the context of the Circular Economy (CE), and significantly informed the theoretical foundation of this study.

The literature review directly supported the exploration of both research questions, identifying barriers and enablers for reusing infrastructure materials and assessing feasible strategies for material reuse. For this study, we adopted a single-case study methodology, focusing on Veidekke Project A, which serves as the empirical foundation for our research. Rather than examining the entire organization (Veidekke), this study looks explicitly at Project A, which involves significant infrastructure development within the Division Infrastructure West in Sweden.

Before starting the study and literature review, we held introductory meetings with an academic supervisor. This helped us refine the research scope, set up the study framework, and identify key focus areas. These discussions laid a solid foundation for the study's aim within the circular economy framework. It also clarified definitions by encouraging an exchange of ideas about circular economy principles, such as reuse, recycling, and sustainability in infrastructure projects. Additionally, this helped us figure out which infrastructure projects were suitable for reuse in the case study. We then created a detailed case study proposal to clarify the research focus. This proposal included topics of interest and a timeline. It guided us in forming research questions, problem statements, objectives, and methods. Ongoing discussions with academic supervisors gave us structured feedback. This feedback helped us refine the research focus, organize themes, and improve our methods.

After setting up the research framework, we looked at relevant literature and created interview questions. Most interviews were pre-planned, but we held two additional interviews on the spot after finding key industry professionals through networking. These experts provided valuable insights on material reuse. Early findings influenced the study's direction. For instance, the study initially included asphalt, but interviews revealed that asphalt is mostly recycled rather than reused. This insight caused us to change the focus of the study. The interview process had two rounds. The first round assessed the current state of material reuse in infrastructure projects. The second round explored future uses of reusable materials. Working with academic and company supervisors, we identified key stakeholders as potential interviewees to ensure we gathered useful data. We mostly sent invitations by email, and all interviews followed a semi-structured format. This approach allowed for flexible but consistent discussions. While we had specific topics in mind, the questions could be asked in different orders, letting interviewees share their thoughts freely.

3.2. Case study

Veidekke is one of Scandinavia's leading construction companies, focusing on advancing sustainable practices within the industry. Veidekke has strategically aligned its operations with the goals of the Paris Agreement, targeting net-zero emissions by 2045. Some of the company's significant milestones are achieving a 50% reduction in greenhouse gas emissions from its operations (Scopes 1 and 2) by 2030 and transitioning its asphalt production processes to reduce emissions by 40% (Veidekke annual report 2024). For instance, the circularity rate in Veidekke totals just 2.4% for Norway, 3.4% for Sweden, and 4% for Denmark (compared to 7.2% globally) (Veidekke Annual Report, 2024). In other words, most resources used to meet societal needs in Scandinavia are not reintroduced to the cycle. This observation highlights an apparent disparity between their goals and sustainability reports (Alam Sidiqqi, 2023). Besides, according to Veidekke's annual report, almost 40% of Greenhouse gas emissions generated by Veidekke are related to the infrastructure division. The company reported Scope 3 emissions of approximately 344,101 tonnes in the infrastructure division in 2023, representing significant emissions from materials like concrete and steel. These statistics highlight the urgency of improving resource efficiency and promoting circular economy strategies in the company, especially in the infrastructure sector.

3.2.1. The case

Single case studies are widely utilized in the construction industry research because they provide an in-depth analysis of complex phenomena within real-world contexts. Furthermore, single case studies can serve as strong evidence to challenge or validate existing theories. Additionally, single case studies enable researchers to explore unique or representative cases in detail (Kedir et al., 2023). Project A, rather than Veidekke, constitutes the empirical case in this study. The project serves as a lens through which circular economy strategies and sustainability practices in large-scale infrastructure projects can be examined in detail. The rationale for selecting a single case lies in the project's potential to provide deep insights into how sustainability objectives are operationalized at the project level. Project A was explicitly selected because it is representative of the kind of complex, large-scale infrastructure developments that carry high environmental impact and are thus critical for achieving meaningful sustainability outcomes. Its combination of technical complexity, stringent environmental requirements, and contractual structure makes it an exceptionally informative and relevant case for study.

Project A serves as the empirical case study for this thesis. Division Infrastructure West conducts this project. It is a large-scale infrastructure project in Sweden designed to enhance traffic flow, safety, and public transport connectivity. The project entails the reconstruction of key interchanges on a major roadway to facilitate smoother and safer traffic conditions, upgrading local streets to accommodate future urban development, and the expansion of a railway line to improve regional train services. Moreover, a new commuter train station is being constructed to facilitate seamless travel across different parts of the city. Project A is highly complex in execution, necessitating extensive expertise in project management and experience in managing large-scale road and utility infrastructure. A complete replacement of existing utilities, including outdated pipelines and drainage systems, is planned to meet the future demands of the area. The construction is scheduled to commence in early 2025 and is expected to be completed by 2030. The project scope includes approximately 1 km of roadway, five bridges, 1.5 km of double-track railway, central district heating infrastructure, and the installation of water and sewer pipelines.

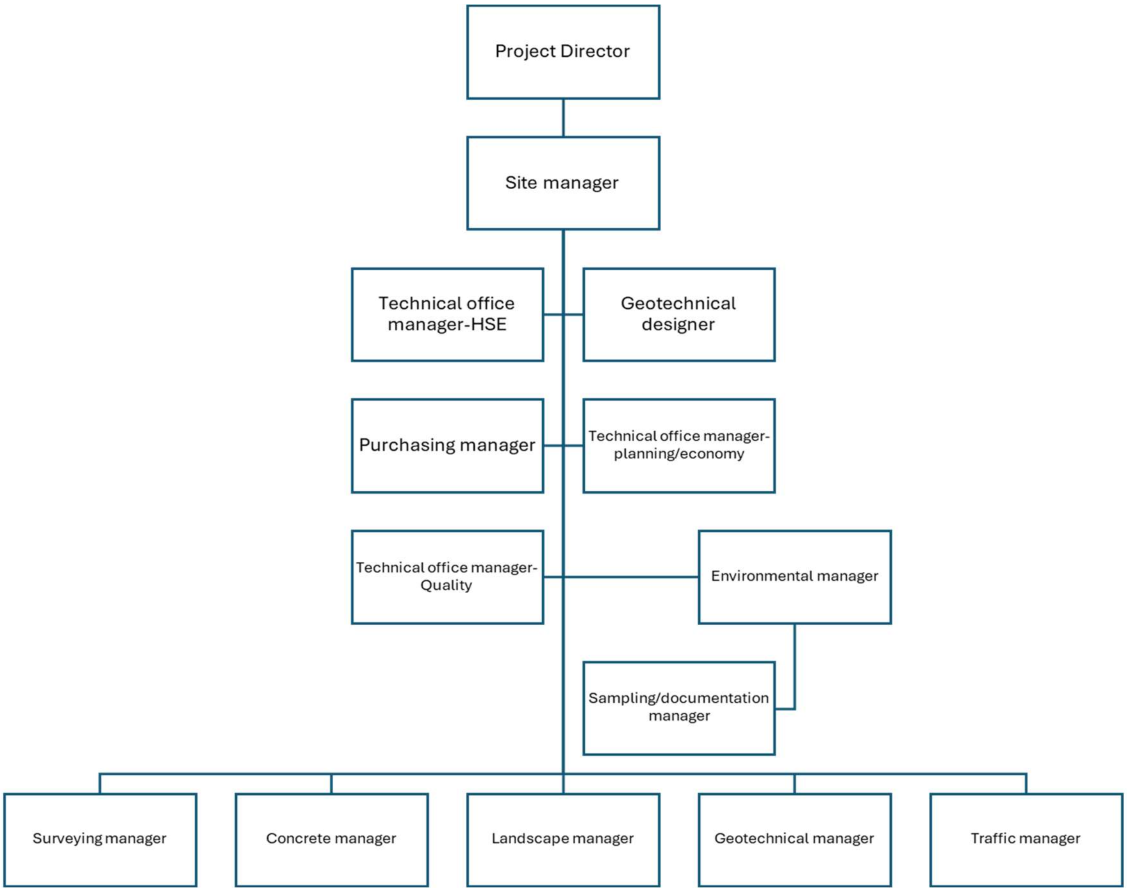


Figure 3.1 Contractor Organization for Project A

The project organization(see Figure 3.1) is structured to ensure efficient coordination across various technical and operational disciplines. At the top is the Project Director, responsible for overall leadership, followed by the Site Manager, who oversees daily execution and coordination. Supporting roles include managers for health, safety, and environment (HSE), quality, planning/economy, and procurement. Specialized roles such as the Geotechnical Designer and Environmental Manager contribute technical expertise, while execution on the ground is managed by field-specific leads, including the Surveying, Concrete, Landscape, Geotechnical, and Traffic Managers.

A key challenge in this project stems from its location, which was historically used for industrial waste disposal. As a result, extensive environmental considerations and mitigation measures are required, with strict execution methods and restrictions imposed by the client. Furthermore, much of Gothenburg is underlain by soft clay with insufficient bearing capacity for heavy traffic loads. The project will employ deep stabilization techniques using cement and limestone to address this geotechnical challenge.

Project A is being delivered under a Design-Bid-Build (DBB) contract (performance contract), meaning that the contractor is solely responsible for executing the construction work using the detailed drawings and technical specifications provided by the client. The tender documents for the project were prepared by the client in collaboration with the designer. The procurement process incorporates specific climate-related initiatives to reduce the project's environmental impact. Notably, the client has set explicit sustainability requirements within the project documentation, including the mandatory use of climate-improved reinforced concrete (RC) for cast-in-situ applications and the specification of low-carbon reinforcement steel. However, to encourage environmentally sustainable practices, the client has introduced an environmental bonus system, offering incentives to the contractor for proposing viable solutions that contribute to environmental impact reduction.

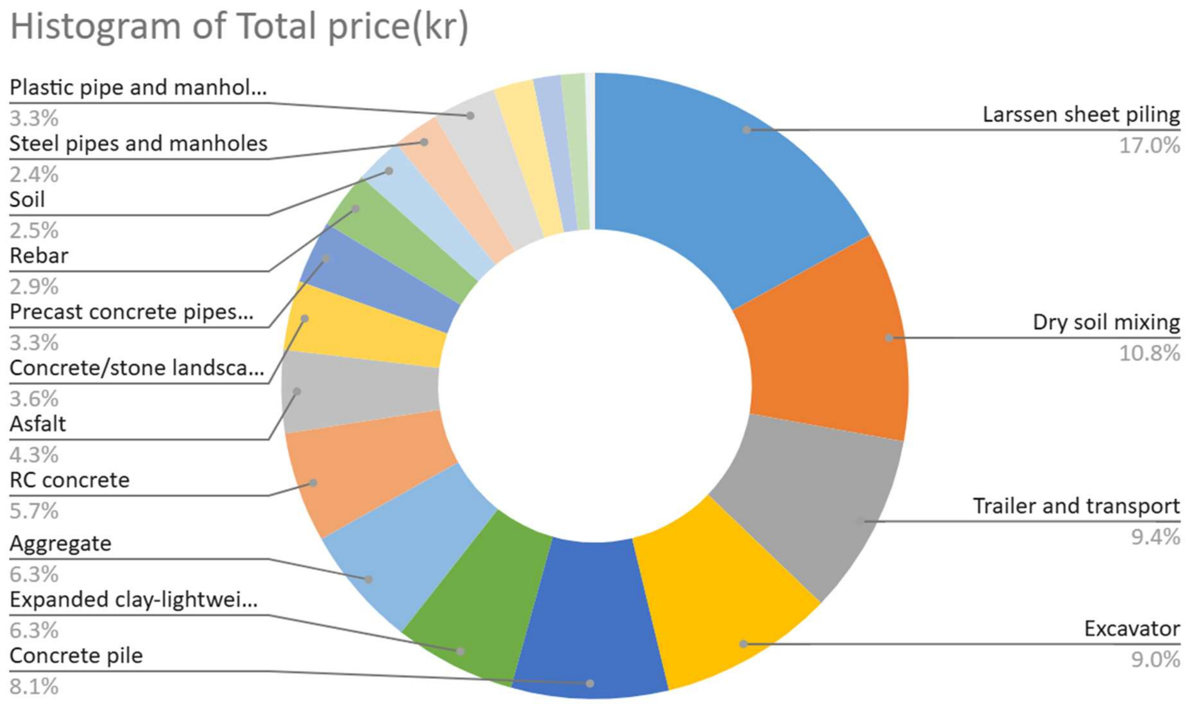


Figure 3.2 Project A total material cost (Veidekke)

The chart (see Figure 3.2) provides an overview of the major cost components in project A. It shows that a significant portion of the budget is allocated to foundational and structural activities such as sheet piling, dry soil mixing, and excavation. Transport and equipment use also represent notable cost areas, reflecting the scale and logistics involved in the project. In addition, various construction materials, including concrete, aggregates, asphalt, and piping, make up a considerable share of the total expenses. Overall, the chart highlights the key cost drivers and offers a clear view of where resources are most heavily invested, which is important when exploring opportunities for material reuse and cost efficiency. The total cost represented in the chart is approximately 500 million SEK.

3.2.2. Collection of data

This study employed a qualitative research approach, which is used to explore and understand social phenomena by analyzing non-numerical data such as interviews (Chapman et al., 2015). Interviews are a widely used qualitative research method for collecting in-depth data on participants' experiences, perceptions, and attitudes. They involve direct interaction between the researcher and the participant, allowing for a detailed exploration of complex topics (Dursun, 2023). For this study, semi-structured interviews were conducted to provide flexibility while ensuring key themes were addressed. The interviews followed a structured framework as a foundation for all participants, but the questions were slightly modified based on the respondent's position and department to ensure relevance. This approach allowed for tailored discussions while ensuring consistency across all interviews.

Interviewers(see Table 3.1) were selected based on their direct involvement in Project A within Veidekke Construction Company and the broader infrastructure sector in Sweden. The interviewees included internal stakeholders, such as head office employees and utility project workers, including environmental managers, project managers, groundwork specialists, technical office managers, business developers, and supervisors. These individuals were chosen for their direct engagement in material procurement and handling, for providing valuable insights into on-site practices and challenges. In addition to internal participants, external stakeholders were interviewed to gain a broader industry perspective. These included consultants, such as design managers responsible for infrastructure planning, and representatives from regulatory bodies, such as those in the client/transportation department. Their insights were crucial in understanding policy constraints, design limitations, and regulatory requirements affecting material reuse in infrastructure projects.

Furthermore, interviews were conducted with key external experts identified through professional networking, including the director of material design at RISE and the Head of ReCreat, who specialize in material reuse and sustainable construction practices. Their contributions provided a broader industry perspective, highlighting emerging trends, technological advancements, and potential strategies for improving material reuse. This multi-stakeholder approach ensured a comprehensive exploration of the barriers and enablers of material reuse in infrastructure projects. By integrating perspectives from multiple levels of project execution, organizational management, industry consultancy, and policy, the study ensured a comprehensive understanding of the barriers/enablers and strategic possibilities for material reuse in infrastructure. This data triangulation strengthens the study's foundation for developing a practical and effective framework for material reuse implementation.

Table 3.1 List of interviewees with information

Company	Interviewees participant code	Role	Year of Work Experience	Interview length	Interview place
RISE	P1	Director Material Design/Dep. Infrastructure and Concrete Technology	11	1 hour	On place
KTH	P2	Head of ReCreat	25	1hour	Online
Veidekke	P3	Environmental manager	23	45min	Online
Veidekke	P4	Project manager groundwork	16	45min	Online
Veidekke	P5	Technical office manager	28	45min	Online
Veidekke	P6	Design manager	8	45min	Online
Trafikverket	P7	Client/Transportation department	20	1hour	On place
LECA	P8	Supplier of lightweight aggregates	20	1hour	Online
Trafikverket	P9	Client/Transportation department	20	1hour	On place
Region Halland	P10	Change/process management leader	16	45min	Online

3.2.3. Data analysis

The data collected for this study were analyzed using thematic analysis, a widely used method for identifying, analyzing, and reporting patterns (themes) within qualitative data. This method enables researchers to organize and describe a data set in rich detail and to interpret various aspects of the research topic (Braun & Clarke, 2006). Thematic analysis was particularly well-suited to this study's objectives of exploring the enablers, barriers, and strategies for reusing materials in infrastructure. The analysis followed the six-phase framework proposed by Braun and Clarke (2006), which involves familiarizing oneself with the data, generating initial codes, searching for themes, reviewing themes, defining and naming themes, and producing the final report. Through iterative reading, note-taking, and coding, this process identified recurring patterns and more profound insights (Fuchs, 2023).

A hybrid approach to thematic analysis was employed, combining both inductive (data-driven) and deductive (theory-driven) techniques (Dejonckheere et al., 2024). While concepts from existing literature guided initial coding, codes were also developed inductively to capture unanticipated or contradictory themes that emerged directly from the participants' responses. This approach enabled the integration of theoretical frameworks and new empirical findings, making the method particularly effective for this abductive study. The thematic analysis process was also supported by NVivo 15, a qualitative data analysis software tool that facilitates the organization, coding, and management of large volumes of textual data. The software helped ensure consistency in coding and provided a structured platform for comparing, refining, and linking themes across interviews.

The analysis began with repeated readings of ten interview transcripts and a review of relevant literature to achieve immersion in the dataset, enabling initial impressions and potential links to the research objectives. Meaningful segments of semantic content were then systematically coded in NVivo using a research question–driven approach, with descriptive labels assigned following the "single response line" method. Both inductive (data-driven) and deductive (theory-driven) strategies were employed to capture emerging insights while remaining grounded in the research aims. Related codes were collated into potential themes by identifying patterns of shared meaning, with deductive themes providing initial structure and inductive themes emerging directly from the data. These themes were reviewed and refined to ensure internal coherence, merging overlapping ones, discarding weak or unsupported ones, and subdividing rich themes where appropriate. Once a stable thematic structure was achieved, each theme and sub-theme was clearly defined and named to reflect its scope, focus, and practical relevance to material reuse in infrastructure projects. The final analytic narrative integrated thematic findings with illustrative quotations, resulting in four main themes and associated sub-themes that form the conceptual foundation for the proposed practical framework.

3.2.4. Evaluation of data

Qualitative research produces substantial data that must be carefully analyzed and evaluated by the researchers. Therefore, selecting an appropriate analytical method is crucial. This study used a thematic analysis approach to examine the collected qualitative data. For the research team, this involved thoroughly reviewing the material, coding the data, and developing meaningful themes (Bryman, 2018).

Once the themes were identified, particular attention was given to three key observations. First, recurring patterns in the data were considered significant, as they could indicate common approaches, barriers, and driving factors mentioned by respondents. Second, identifying respondents' similarities and differences was essential for shaping the themes. Third, unanswered questions were also valuable observations, providing further insight into how different contractors approach reuse (Ryan & Bernard, 2003).

After establishing various themes, the next step was prioritizing them based on their relevance to the research objectives, and relationships between the identified themes were explored to determine potential connections (Bryman, 2018). Thematic analysis has both advantages and disadvantages. One key advantage is its flexibility, as it is not restricted by predefined theories, allowing researchers to generate themes that are most relevant to the study. Another benefit is that this method requires a comprehensive analysis of all collected material, ensuring no critical details are overlooked. However, thematic analysis can be time-consuming, and some critics argue that it may lead to data fragmentation, potentially obscuring the overall context (Bryman, 2018).

3.2.5 Ethical Considerations and Trustworthiness

This study strictly adhered to ethical principles, ensuring respect for all interviewees. Participants were fully informed about the study's purpose, and their interviews would be recorded. Consent was obtained before any recordings took place. Each interviewee was briefed on the study's objectives and explicitly asked permission to share their profiles, roles, and relevant information. Direct quotations from the interviews are attributed to the respective participants with their consent. Additionally, approval was obtained for the publication of the final report. Ensuring voluntary participation and securing permission for recording were key ethical priorities throughout the study. Finally, the study's results and recommendations align with the ethical framework of Chalmers University of Technology.

To be considered trustworthy, qualitative research must demonstrate that data analysis has been conducted precisely, consistently, and exhaustively. This involves systematically recording, organizing, and clearly articulating the analytical process to allow readers to assess its credibility (Nowell et al., 2017). In this study, several strategies were employed to enhance Trustworthiness. Triangulation was used to collect data from diverse stakeholders, including internal staff, external consultants, clients, and researchers. This approach ensured a comprehensive perspective on the research topic. Member checking was conducted during selected interviews to confirm that participants' views were accurately understood and represented. Additionally, the study emphasized methodological transparency, providing a clear and detailed explanation of how data were collected, coded, and thematically analyzed. These measures collectively strengthen the credibility, dependability, and transferability of the findings, ensuring the research process is rigorous and replicable.

3.2.6 Limitations of the Study

This study was based on a literature review and interviews. The results from both the literature review and the interviews were closely aligned, revealing similar views and perceptions regarding the concept of reuse, as well as the existing opportunities and challenges. The literature provided broader and deeper insights into the subject, while the interviews focused on critical aspects, offering real-life examples based on the participants' experiences in the industry. There were several limitations to this study. Firstly, using a single case study restricts the generalizability of the findings to other contexts or countries. Secondly, the data collected through interviews may be influenced by participant bias or limited perspectives. Lastly, time constraints and the availability of interviewees meant that certain roles or viewpoints may not have been fully represented.

4. Results

4.1 Introduction

This chapter presents the key findings from interviews with stakeholders involved in the project and professionals from the infrastructure sector. The analysis addresses the main research questions aimed at developing a practical framework to support the reuse of materials in infrastructure projects. Specifically, the study explored the enablers and barriers to material reuse within the infrastructure sector, along with practical strategies for its implementation. The data were systematically analysed and organised into four overarching themes (see Figure 4.1), enablers of reusing infrastructure materials, barriers to reusing infrastructure materials, practical strategies for implementing material reuse, and materials most suitable for reuse in infrastructure. The first three themes include sub-themes that provide a detailed and nuanced understanding of participants' perspectives. The fourth theme, while significant, consists solely of descriptive codes without sub-themes, reflecting participants' views on which materials are most feasible and appropriate for reuse in infrastructure contexts. Together, these findings inform the development of a practical framework and offer additional insights into real-world reuse practices.

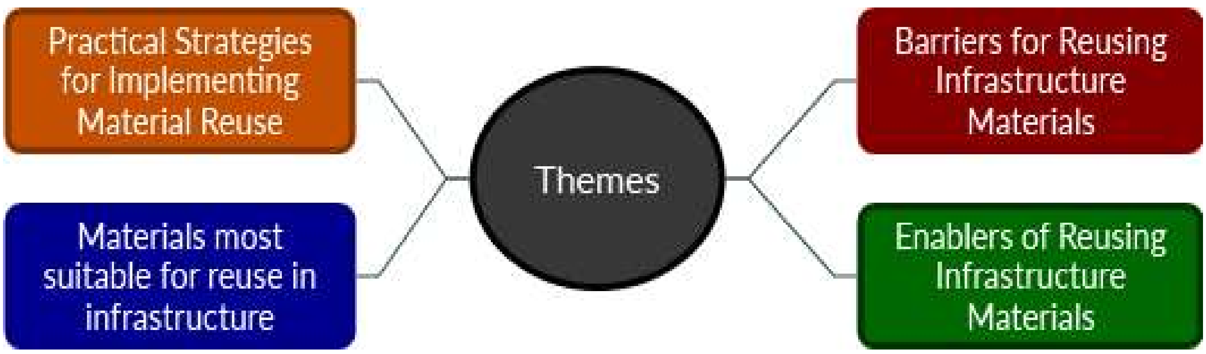


Figure 4.1 Thematic maps of the themes

Overview of Interview Participants: Ten interviews were conducted with experts from within the company, key stakeholders, and professionals with extensive experience in the study area. Interviewees had between 8 and 25 years of professional experience. Several interviewees provided in-depth responses, addressing emerging questions and offering valuable insights. However, some respondents covered only certain aspects of the interview questions, despite their experience in the construction sector, due to having more limited exposure to the specific research area of material reuse. Figure 4.2 presents the coding reference counts for each interview participant.

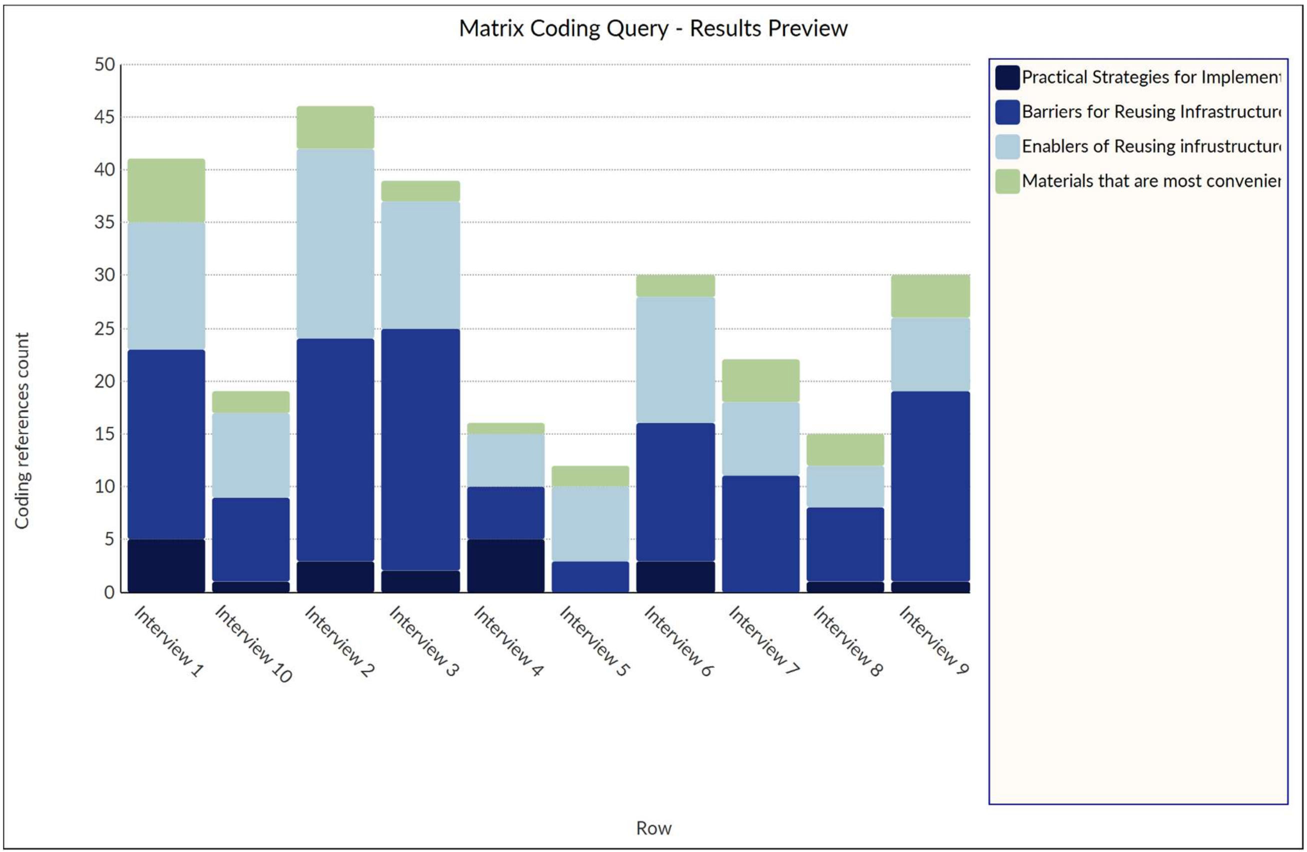


Figure 4.2 Coding reference counts for each interview participant

The following sections examine each of the four main themes in detail, along with their associated sub-themes, supported by evidence from participant interviews.

4.2. Barriers for Reusing Infrastructure Materials

Reusing materials in infrastructure faces several related challenges in regulatory, economic, technical, and operational areas. Outdated regulations, unclear responsibilities, and inconsistent standards lead to complicated and risky compliance problems. Economically, the low cost of new materials and the lack of financial incentives often make reuse unattractive. Technically, reused materials frequently have inconsistent quality and lack proper documentation, which makes them hard to use in current design processes. These processes usually emphasize new materials and seldom consider the availability or characteristics of reused components from the start. Operational challenges, such as poor logistics, limited storage, and a lack of knowledge, also hold back reuse efforts. These factors confine reuse to small, separate projects instead of making it a common practice. Based on our interview findings, we will look more closely at these challenges through four sub-themes.

4.2.1. Regulatory Barriers

One of the significant and complex obstacles to increasing reuse in construction and infrastructure is the presence of strict and outdated regulations. These barriers stem from outdated laws, unclear governance, a lack of standard practices, and rigid contracts, which hinder the successful implementation of reuse methods. The findings indicate that these problems are widespread, impacting every stage from planning and procurement to execution and compliance. Based on our collected data, we could identify multiple obstacles in this area, which will be described in separate sections below.

Outdated and Inflexible Regulations

Interviewees consistently emphasized that existing regulatory frameworks are misaligned with circular economy principles. Most rules, certifications, and performance standards were developed for a linear construction model that uses new materials with traceable origins and uniform properties. This orientation unintentionally disadvantages reused materials, which may not include linear benchmarks, even if they remain technically and functionally safe.

"*The regulations can create obstacles, especially when it comes to permanent products that must meet quality standards for delivery to the client*," mentioned interviewee 1.

For instance, reused structural components often cannot meet current certification requirements due to a lack of official documentation, not because they are unsafe, but because they were not initially intended for reuse or documented for it. The legal and administrative burden of justifying reuse is often remarkably high. This causes many stakeholders to choose new materials instead, even though reuse has environmental and economic benefits.

Bureaucratic and Time-Consuming Approval Processes

Interviewees also described the excessive bureaucracy involved in obtaining approval for reused materials. The reuse process requires extensive documentation, material testing, project-specific permissions, and transparent allocation of responsibilities, all of which make implementation complex and unpredictable.

"*It becomes too much. We'll probably get a no anyway, and then it's not worth putting the energy into it*," mentioned interviewee 3.

Approval procedures in public infrastructure projects are often slow and inconsistent between administrations. Many local authorities do not have updated processes for evaluating reuse, and timelines are uncertain. As a result, stakeholders usually choose new materials because they are quicker and easier to approve.

Lack of Quality Control Standards

A significant challenge is meeting compliance and certification requirements for reused materials when it comes to quality, safety, and performance. Current systems focus on traceability and standardized testing. These features are easier to achieve with newly produced materials. In contrast, reused materials can come from different sources and often lack proper quality control documentation. This makes compliance challenging. For example, reused components usually cannot obtain CE marking, which is necessary for many construction products in the EU.

"*We don't have standardization of how it should be done to assess the quality; every time, it's like an innovation project,*" mentioned interviewee 7.

This mismatch puts contractors and engineers at risk of legal issues and damage to their reputation, especially if reused materials fail inspections or compliance audits later. Because it is unclear who is accountable, stakeholders often avoid reuse altogether. This stifles innovation and leads professionals to select new materials by default.

Governance Gaps and Unclear Responsibility

The governance structure for reuse practices is another key barrier. Interviewees mentioned confusion about who is responsible for approving, overseeing, and ensuring the implementation of reused materials. This unclear division of roles reduces accountability and discourages proactive planning.

"*Someone needs to take the overall responsibility for the reused material,*" mentioned interviewee 3.

In infrastructure projects, various stakeholders like contractors, consultants, and public authorities, a lack of clearly defined responsibilities causes stakeholders to act cautiously. No party wants to assume responsibility; everyone avoids taking the initiative, fearing being responsible if something goes wrong, which results in collective inaction and a return to linear construction practices.

Contractual Framework Limitations

Interviewees also identified structural limitations in standard contracting models, particularly Design-Bid-Build (DBB). In this type of contract, project designs and specific material specifications are defined before the contractor gets involved. These types of contracts probably reduce the chance of upscaling the reuse.

"*It's not just about regulation, but how the contracts are structured. There's no room for improvisation or flexibility,*" mentioned interviewee 1.

Conventional contracts restrict the flexible planning required for the reuse of material. However, collaborative contract methods, such as Early Contractor Involvement (ECI) or partnering frameworks, are not widely adopted, especially in the public sector. This rigidity makes reuse difficult, even when reclaimed materials are available and suitable.

Inadequate Guidelines

One significant barrier to increasing reuse is the lack of clear, practical, and specific guidelines. Interviewees pointed out that the existing guidelines often overlook circular practices. This can be hard to grasp due to the diverse nature of the construction industry. As a result, there is uncertainty in operations, which raises the risk of errors and discourages innovation.

"*The guidelines we have don't help us with reusing materials. They're written for standard projects, not for when you're trying something different*," claimed interviewee 6.

Well-established guidelines are essential in the infrastructure sector due to the high level of requirements for products during the tender stage.

Lack of Stakeholder Coordination

Interviewees mentioned a barrier created by the lack of coordination among key stakeholders, including government authorities, contractors, consultants, and material suppliers, while this fragmentation limits the ability to adapt for reuse. Without strong leadership from national or local authorities, organizations often work in isolation, each concentrating on its specific goals rather than looking at the broader potential for reuse across the system.

"*There's no one who takes the lead. Everyone does their part*," mentioned interviewee 2.

This lack of coordination makes it hard to develop shared best practices, set goals, or push for policy changes. Reusing materials for major infrastructure projects requires clear communication to help with planning and implementing the reuse.

4.2.2. Economic and Market Barriers

Economic and market constraints emerged as the most significant barriers to material reuse in infrastructure and construction projects. While material reuse, environmental, and sustainability benefits are well recognized, their financial viability remains a considerable hurdle. The economic aspects of the construction industry, including the costs of collection, transport, testing, and certification, often make reused materials less competitive than new ones. This section examines stakeholders' main economic challenges when considering material reuse in construction projects.

Cheap Virgin Materials

The availability of inexpensive new materials, especially in infrastructure projects, creates a significant obstacle to reusing materials. In today's market, the costs of new materials are often lower than the total expenses of collecting, transporting, testing, and certifying reused materials. This price difference weakens the financial argument for reuse, particularly in projects with tight budgets.

"*It's the price of a news product; it's not expensive enough to make us interested in reuse,*" mentioned interviewee 10.

This reflects the fact that virgin materials, in many cases, are priced so competitively that the additional logistical, regulatory, and quality control costs associated with reused materials make them economically unattractive. Even when reuse is technically possible, the low price of new materials makes it less appealing from a short-term economic viewpoint.

High Costs of Material Recovery

Interviewees mentioned that substantial operational costs associated with dismantling, transporting, and reprocessing materials could reduce the possibility of reusing materials, depending on the project-specific situations. In some infrastructure projects, dismantling old structures and collecting reusable materials requires extra labor, the cost of analysis, specialized equipment, and strict quality control measures.

As interviewee 8 mentioned, "*If the reused material has a lot of dirt, we must separate it to reuse again, that is the cost and additional time.*"

This shows that the high cost of material handling often outweighs the potential savings from using reclaimed materials. The challenge becomes even higher in case material recovery processes are needed to match the strict schedules of current projects.

Limited Market Size and Investment Risks

Interviewees expressed worries that the market for reused construction materials is not fully developed, is fragmented, and is seen as too small to attract significant investment. This small size leads to a cycle where low demand discourages investment, and a lack of investment hinders market growth.

"*The market is too small to jump on it!*" mentioned interviewee 1.

Many contractors and developers hesitate to invest in reuse due to the unpredictable supply and inconsistent quality of reused materials. The absence of established marketplaces or platforms for sourcing and selling these materials adds to this uncertainty. Moreover, participants noted that reuse is rarely a priority in procurement policies. This reduces its competitiveness in public or private tenders.

"*Contractors are not incentivized to develop excellent proposals unless it bring some return. It's nice to say it's for the environment, but unfortunately, that's not a strong enough driving force,*" mentioned interviewee 4.

This shows a common view that people value environmental sustainability, but it does not have the financial support needed to change industry practices.

Lack of Viable Business Models

The absence of scalable and strong business models further increases the economic challenge of reuse. Interviewees noted that while some niche businesses and pilot initiatives have demonstrated the technical feasibility of reuse, few have proven financially sustainable in the long term.

The key problems are inconsistency, infrequent demand for reused materials, fragmented supply chains, and low market awareness. In this context, businesses operating in the reuse space are exposed to significant financial risk, and few succeed in developing profitable operations.

"*There is no comprehensive or universally accepted business model that can be applied across different sectors and projects,*" mentioned interviewee 2.

This lack of standardization makes it harder for demolition contractors, reuse facilitators, and construction companies to work together. The uncertainty in supply and demand means that even the best-intentioned reuse programs find it challenging to build a steady revenue base. Consequently, many businesses focused on reuse work in a high-risk, low-margin setting with few chances for growth or expansion.

Complexity in Procurement Processes

Another barrier identified relates to the administrative and procedural complexities involved in integrating reused materials into formal procurement systems. Particularly in large-scale infrastructure projects, procurement frameworks are rigid and often fail to accommodate the unique reuse requirements.

"*In a business setting, we need contracts, agreements, and the right procurement processes that add complexity,*" mentioned interviewee 3.

Standard procurement models usually focus on cost efficiency, certainty, and compliance. Conventional contracts often overlook materials that introduce variability or require additional coordination. This inflexibility can prevent the reuse from being scaled up and lead to the need for special contracts and stakeholder agreements.

4.2.3. Technical Barriers

Technical-related barriers remain among the most persistent challenges limiting the practical implementation of material reuse in the construction and infrastructure sectors. These barriers significantly hinder practical implementation. Insights from the interview participants consistently highlighted that technical uncertainty and a lack of integration into design processes make reuse complicated and often risky.

Inadequate Documentation

Interviewees widely recognized a lack of accurate documentation and uncertain quality as a significant barrier to reuse. Without reliable records that show a material's origin, composition, clear testing or classification methods to check its condition, and compliance with relevant standards, stakeholders were reluctant to trust reused materials. This gap harms both quality assurance and regulatory compliance. Interviewee 5 noted, "*Following up on the documentation and digitalization is difficult.*" The problem is particularly acute in infrastructure projects, where many components, mainly underground utilities, are undocumented or embedded in outdated systems. This creates additional complexity when integrating reused materials into new projects. "*Often, we lack production documentation or even drawings of the building. It's pretty challenging in this regard*," claimed interviewee 2. Basic information, like the source of materials or the standards they meet, is often missing. Without organized digital documentation systems, decision-making takes longer and sometimes is impossible.

In addition to documentation, evaluating reused materials' lifespan is difficult, especially for those exposed to harsh outdoor conditions, like bridges or parking structures. This uncertainty makes it hard to predict their long-term performance. Contamination from pollutants or dirt, especially in materials recovered from industrial sites or gas stations, requires extra cleaning and verification steps. As interviewee 7 illustrates, "*How do we determine the remaining lifespan? This is even more difficult than building components*." These combined factors of heavy physical handling, quality uncertainty, and contamination increase technical and financial burdens.

Design Process Limitations

Several interviewees emphasized that reuse is rarely considered during the early design and planning stages. In most cases, the design process follows a straight path. Plans are made with the idea that new materials will be used. As a result, reused materials, when they are considered, are usually brought in late in the process, after the key design choices have been finalized. This late-stage inclusion usually results in poor alignment between available reused materials and the finalized design, leading to missed opportunities or the need for costly adjustments.

Moreover, many existing building elements were never designed with reuse in mind. This makes disassembly, reconnection, and integration more difficult, turning each reuse effort into a one-off challenge. "*We lack technical solutions for integrating components collected from other projects. Every project is treated as an innovation project,*" mentioned interviewee 1.

Logistics and Storage Limitations

Reused materials in infrastructure projects pose unique handling challenges that complicate their use. Many components, like large concrete pieces, steel beams, and aggregates, are heavy and bulky. They need special equipment, careful planning for safe removal, transport, and handling. These logistical challenges raise costs and require coordination beyond typical construction processes.

Logistics has become one of the most common obstacles to reuse, especially when coordinating material availability, transportation, and temporary storage. Most infrastructure construction projects follow a just-in-time delivery model, which offers little flexibility to handle reused materials that often become available outside the project's ideal timeline. Timing mismatch creates operational friction, especially since most projects lack the infrastructure for interim storage. In several cases, valuable reusable materials are discarded not because of poor quality, but simply due to the absence of space and time to store them. Interviewee 2 illustrated this by stating, "*We would need an empty city somewhere*" to store bulky infrastructure components. The pressure from tight schedules, limited storage, and a lack of coordination creates a significant hurdle in logistics.

Mismatch Between Projects

A significant obstacle to reusing materials is the gap between dismantled materials and the needs of new construction projects. Reused components often come from projects with different specifications, which makes it hard to fit them into new designs. Variations in dimensions, standards, and connection details frequently make potentially valuable materials incompatible with the new project. Several interviewees described this integration component as challenging and lacking compatibility. Furthermore, public-sector infrastructure projects often have strict rules about visual and performance criteria, which makes it harder to use reused materials. As interviewee 5 said, "*They have specific requirements for how things should look, so I doubt anything other than a new product would be accepted.*" These differences in specification and performance limit flexibility and increase dependence on new materials.

4.2.4. Societal and Knowledge-Based Barriers

Societal attitudes and knowledge gaps play a significant role as barriers to material reuse in the construction and infrastructure sectors. Unlike technical or economic obstacles, social and knowledge about the reuse can be a significant drawback and hinder the reuse principles. These issues directly impact daily project workflows and stakeholder interactions. Moreover, these challenges exist even when there is a strong motivation and policy support for reuse.

Lack of Knowledge and Expertise

Another theme from the interviews was the lack of knowledge and technical expertise regarding reuse practices. Several key stakeholders, including procurement officers, architects, and engineers, often lack the necessary competency and experience in managing reuse processes. This skills gap limits their ability to specify, design, and integrate reused materials.

Interviewee 9 mentioned, "*A few people know how to do it. Knowledge could be a problem, especially in the early stages.*"

This highlights two important issues. In the early stage of the project, particularly the planning and designing phases, having the right knowledge is crucial for incorporating reuse thinking and minimizing mistakes. If the reuse ideas come later or if the right information is missing or delayed, it becomes harder to correct mistakes later, especially in large infrastructure projects. Additionally, this scarcity of expertise means that the responsibility for reuse often falls on a small group of specialists. This creates a dependency on specific individuals, and if they leave, it can hinder the project. These challenges indicate a need for more industry training and better knowledge sharing across teams.

Negative Perceptions and Societal Bias

Society's perspective on reused materials represents another significant barrier. Several interview participants noted that people often see reused materials as less reliable than new ones. Interview 5 remarked, "In society, we still don't see reused material as just as good as new." This perception influences decision-making by contractors, consultants, regulators, and clients, keeping a preference for virgin materials despite the potential benefits of reuse.

This perception also influences how society accepts the principles of a circular economy. Several interviewees raised concerns about the ethical and social effects of reuse strategies. Often, these efforts depend on materials taken from poor or marginalized communities, turning them into so-called "material banks." This can lead to negative emotions, as these communities may feel used or neglected. Instead of being seen as partners in sustainability, they risk being treated like dump sites or secondhand sources. Interviewee 8 expressed concern that "*Using poorer areas as material banks creates resistance and stigma, making it harder to gain community support for reuse projects.*"

Cultural and Industry Barriers

The construction and infrastructure sectors are based on traditional, linear production models. Moving towards circular reuse involves a significant cultural and operational change. Interviewee 6 stated, "*The shift is as large as going from a craft-based society to an industrial society, moving from industrial to circular economy.*" This transformation is naturally slow and complicated. Interviewee 4 reflected, "*It is one of the slowest industries to change,*" pointing out the strong resistance from established routines, fear of risk, and strict regulations. Overcoming this barrier requires not only technical innovation but also a cultural shift that redefines quality, risk, and value in material sourcing.

4.3. Enablers of Reusing Infrastructure Materials

Reusing infrastructure materials involves a more coordinated approach that combines design, economic, technical, and cultural aspects. Insights from interviews with industry professionals emphasize the importance of early planning in successfully implementing material reuse. This also requires supportive regulations, effective collaboration, and a shift in mindset among all stakeholders. This section presents the key enablers identified through the interviews, organized into four interconnected sub-themes. Design integration and flexibility, organizational capacity and culture, Technological tools and material flows, governance and market enablers.

4.3.1. Design Integration and Flexibility

A central theme in the interviews is the critical role of design integration and flexibility in allowing material reuse in construction projects. Interviewers consistently noted that design choices made early in the project lifecycle greatly affect whether reuse can be successfully achieved. Specifically, adaptable and modular design methods, transparent and standardized processes were essential for incorporating reclaimed materials. Rather than treating reuse as an add-on to old design processes, interviewees advocated for a more circular design mindset, in which project plans evolve based on the characteristics and availability of secondary materials. This section presents key subthemes illustrating how design-stage decisions can facilitate or constrain reuse.

Early Consideration of Reuse

Findings from the interviews show that bringing reuse considerations into the design phase early is key to successful implementation. Many participants highlighted that reuse cannot be effectively pursued if it is considered too late in the project timeline. After a project's design is finalized, there is little flexibility to include reused materials. Interviewers noted that starting reuse discussions during the conceptual design stage helps better match available secondary materials with project needs. This proactive approach shifts the linear design logic, where materials are selected to suit a predetermined design, toward circular reasoning in which the design evolves based on the characteristics of available reused components.

As interviewee 3 explained, "*Reuse needs to be in the design from the start,*" which underlines the importance of addressing material availability before imposing design constraints. Similarly, interviewee 2 mentioned "*Design needs to adapt to what is available*", which reinforces that reuse-driven projects require a more flexible, responsive design process.

Standardization and modularization

Interviewers strongly suggest that standardization and modularization can be the two main enablers for the reuse of construction materials. Standardized components, such as beams, columns, and slabs, that are designed with uniform connectors and dimensions, have a greater potential for reuse in new construction. As interviewee 2 noted, "*If there are components that are standardized in terms of certain connectors or dimensions, this facilitates reuse because they can fit into new construction.*"

Another main enabler emphasized by participants was modularization, which they identified as a critical design strategy that supports material reuse. This approach involves designing structural and architectural elements, such as beams, walls, and columns, based on consistent base units or modules. Interviewee 2 explained that "*Modularization, especially in architecture, is based on a consistent module. For example, your kitchen cabinet might be 60 centimeters wide and 90 centimeters high, and a bed from IKEA might be 90 centimeters wide by 210 centimeters long, both divisible by 30 centimeters. This modular logic is also reflected in structural components, which follow the same principles.*" By incorporating standardized and modular design principles in the construction process, components can be easily reused in new projects.

In addition, participants highlighted the importance of designing for disassembly, which intentionally creates buildings in a way that enables components to be taken apart without being damaged. As interviewee 5 stated, "*Design for disassembly is key for future reuse*". This approach makes dismantling easier and allows valuable materials to be reused more efficiently in other projects.

Develop Guidelines

Several interview participants emphasized the critical need for clear, standardized guidelines that support the reuse of construction materials. The lack of such guidelines often results in inconsistent practices among stakeholders, creating barriers to effective implementation. Developing standardized and common guidelines addresses this issue by facilitating the integration of reused materials into construction projects. Such a framework also fosters a shared understanding among stakeholders and supports consistent decision-making across different project phases.

As interviewee 6 noted, “*Clear guidelines would reduce the friction,*” which reflects how shared regulatory frameworks can enhance collaboration and promote reuse practices.

4.3.2. Organizational Capacity and Culture

Enhancing sector expertise, competency, and capacity for material reuse, with the establishment of reuse as a norm among stakeholders, supports the treatment of reused materials as equivalent to new ones. Fostering a circular mindset and embedding reuse into organizational culture were seen as essential for long-term transformation. This section discusses some of the interconnected themes that emerged from the interviews.

Clear Roles and Responsibilities

The interviews showed that successfully using reuse practices in construction projects relies heavily on having clear roles and responsibilities. Projects where organizations with specific reuse coordinators or dedicated teams were better at incorporating reused materials into the design and construction process.

Several participants emphasized that the absence of assigned responsibility for reuse leads to being overlooked during a project. As interviewee 3 mentioned, "*Without someone owning the role, it doesn't happen or affects the adaptation process.*" This emphasizes the importance of having formal responsibility structures within project teams.

Education and Training

Education and training are important for giving people the skills they need to work with reused materials. Many interview participants said that training helps increase awareness and understanding of reuse, which can lead to better rules and better use of reused materials in projects.

Some interview participants also pointed out that teaching students about reuse early on can change both current practices and future ways of building. As interviewee 2 explained, “*At first, I noticed that they're not educated to deal with a building site that already contains material, but at the end of the year, it's no problem, they are just as good architects, but they're just working in a slightly different manner.*” This shows that with the right support and practice, people can quickly learn how to work with reuse in construction.

Stakeholders’ Collaboration

Collaboration among stakeholders is essential for the successful implementation of material reuse in construction projects. The construction industry involves multiple stakeholders and areas of expertise within an interconnected organizational structure. As a result, the adaptation of reused materials requires cross-disciplinary coordination throughout all project phases. Interview participants mentioned that early collaboration between main actors of the sector, such as clients, architects, engineers, and contractors, increases the opportunity to integrate reused materials by developing shared planning and vision.

Multiple interview participants also mentioned that clients should take responsibility for the implementation of reused materials in the sector. When clients prioritize reuse practices, other stakeholders are more likely to align in their work. As interviewee 3 noted, “*When the client prioritizes reuse, the rest of the team gets on board.*” This suggests that collaboration is more effective when there is clear leadership from the top.

Taking the Circular Economy as a Norm

Making Circular Economy (CE) principles an organizational norm is important for every project implementation of reuse, like how regular linear construction materials are used. Interview participants mentioned that organizations with a strong internal commitment to CE principles, especially reuse, are more willing to put effort into exploring reuse solutions and moving toward broader adoption. This emerging norm within organizations supports the proactive identification of reuse opportunities and helps reduce resistance to change.

In addition, organizations with previous experience in reuse projects have better capability to manage uncertainty and contribute to the normalization of reuse practices within teams and among stakeholders. Moreover, taking CE principles as a norm may no longer be a choice, it could become essential for organizational survival. As interviewee 9 stated, "*Circularity isn't just a project, it's how we do business.*"

4.3.3. Technological Tools and Material Flows

The interview findings highlight the importance of technological tools and material flow management in facilitating the reuse of construction materials. Successful reuse implementation relies significantly on having the right tools and systems in place. Interview participants strongly emphasized the need for strong storage and logistics solutions to connect the time and space between demolition and new construction. They also stressed the growing importance of digital tools, especially material passports and online platforms, to enhance transparency, traceability, and trust in reused materials. This section describes these aspects in detail.

Storage and Logistics Support

Storage and logistics infrastructure are essential for improving material reuse in construction. A common challenge noted by participants was the timing mismatch between demolition and the new building. This often results in losing reusable components because temporary storage facilities are unavailable. Interviewee 6 mentioned, "*Without temporary storage, reuse often fails,*" highlighting how short-term storage solutions can be a significant obstacle, even when valuable materials are on hand.

Additionally, having large-scale storage areas was viewed as a key advantage. Interviewee 2 pointed out, "*We focus heavily on reuse because we have large areas available,*" indicating how physical space supports systematic reuse efforts.

Interview participants frequently stressed that access to dedicated storage offers greater flexibility and efficiency in reuse workflows. Interviewee 8 explained, "*Storage allows flexibility between demolition and new build.*" This separation makes reuse more effective, eliminating the need to coordinate demolition and construction activities perfectly in time.

Some interviewees described direct logistics plans, where materials are moved straight from one site to another. However, these strategies still required intermediate quality checks to ensure material suitability. As interviewee 2 noted, "*The plan is to take it from one site, straight to the other construction site. But we have to check the material first.*" Interviewee 1 further elaborated on the need for technical validation, stating, "*We take the density, see the curve, and send it to the environment check to ensure it's not polluted.*"

Several interviewees suggested that getting local governments involved could improve logistical support. Interviewee 3 proposed, "*The municipality should have areas or spaces.*" Interviewee 5 imagined a more coordinated effort between the public and private sectors, stating, "*There should be some joint venture between the municipality and transport government agency.*" These comments show a shared belief in the need for common infrastructure and planning to promote broader reuse.

Interviewees also expressed different opinions on how to organize reuse logistics. Some preferred local, project-based planning, while others saw benefits in larger-scale coordination. Interviewee 2 noted, "*Where will it be more logistically difficult to handle?" So, I believe more in the bottom-up approach in this sense.*"

Material Passport and Digital Tools

The interview findings highlight that material passports, backed by digital tools, are essential for effectively reusing construction materials. Interviewees repeatedly mentioned that the lack of trustworthy and easy-to-access information on material properties, history, and performance is a significant obstacle to reuse. In this context, material passports enhanced transparency, traceability, and informed decision-making throughout the material lifecycle.

As interviewee 1 described, "*Material passports, where all the materials will have their properties built in and it will be possible to track from production to many service lives, during the total service life of the products,*" highlighting the long-term value of such systems in supporting circular construction practices.

Several interviewees emphasized the significance of verified documentation in building trust in reused materials. For example, interviewee 5 stated, "*If there's a test report, I trust the material,*" indicating that data availability greatly influences usability and acceptance.

Another theme from the interviews was the role of digital platforms in centralizing material information and making reclaimed resources more accessible. As interviewee 2 stated, "*Digital reuse marketplace is a game changer,*" reflecting how these tools improve market visibility, accessibility, and efficiency.

4.3.4. Policy and Economic Enablers

Policy and economics play an important role in supporting or hindering construction material reuse. The interviews revealed that strategic mechanisms, such as financial incentives, procurement frameworks, and regulatory measures, are crucial for influencing acceptance and reducing the perceived risk associated with reuse practices.

Financial Incentives

Financial incentives can be used to promote material reuse in construction. Interview participants strongly agreed that, while reuse is good for the environment, it often comes with higher initial costs and more labor involvement, especially during the early phases.

Many interviewees highlighted that financial support from subsidies or tax relief is crucial for reducing economic risks and encouraging reuse ideas. *Interviewee* 4 mentioned, "*Funding helped us to test reuse material,*" which shows how outside financial funding helps organizations to explore circular practices and allows them to develop internal procedures and scale up reuse.

In addition, carbon taxation was also mentioned as a possible long-term support. *Interviewee* 3 explained, "*If there's a carbon tax introduced, then suddenly materials will become valuable as gold; you deal with it more carefully, and then reuse will become more profitable.*" This suggests that applying environmental costs through taxation can change market dynamics, making reused materials more attractive and promoting resource-efficient practices.

Developing Business Models

The development of circular business models can help the construction sector minimize financial risks by organizing services more effectively. This allows companies to generate profit from the reuse of construction materials rather than viewing it as a financial risk.

Interviewee 5 mentioned, "*Business models are shifting the sector, reuse can be the way we make profit.*" This reflects how attitudes toward reused materials are changing due to the potential for financial gain. This shift encourages the growth of specialized companies that focus on reuse-related tasks. Additionally, *Interviewee* 3 described that adopting a "*reuse as a service*" model could increase the service providers. In this model, providers take full responsibility for the reuse process, managing everything from dismantling and documentation to quality control and transport.

Procurement Requirements

Interviewees indicate that public sector clients, particularly municipalities and governmental agencies, can significantly advance reuse practices through procurement strategies. When reuse is listed as a requirement in public tenders or contracts, it encourages construction companies to prioritize the integration of reusable materials. Interviewee 5 explained, *"The tender asked for incorporating reuse within the project, so we prioritized reused material."* This shows that contractual obligations directly influence decision-making during the planning and execution phases. Similarly, Interviewee 7 emphasized that "*Procurement can help drive reuse forward",* underlining the power of procurement as a policy tool.

Quality Assurance

Quality is one of the main constraints in the construction industry. Ensuring the quality of reused material is the main enabler for the adaptation of reused material within the sector. Interviewees generally agreed that quality in reused materials relies on clear evidence of their safety, performance, and compliance with regulations. Many view reusing as too risky or expensive without proper quality assurance testing.

Several Interviewees noted that materials need to be carefully evaluated based on their previous use, as not all materials are equally degraded by their prior use. Some may still be in good condition, while others may not be suitable for reuse. Interviewees also mentioned that proving quality helps make reused materials easier to sell. Interviewee 10 explained, "*You need to use it as* *a selling point, just like being ISO certified. You need to commit."* This suggests that showing material quality can build trust and be a competitive edge in reuse-oriented projects.

4.4. Practical Strategies for Implementing Material Reuse

The second research question focused on identifying practical strategies that enable the implementation of material reuse in infrastructure projects. Through qualitative interviews with industry professionals, it was evident that although people generally support the idea of reuse, putting it into practice needs structured methods that fit the needs of large-scale construction settings. This section combines those insights into three main themes of reuse strategies. Each theme presents different ways to include reuse in infrastructure workflows.

From the interviews in the study, participant 1 noted that material reuse is not a one-size-fits-all solution *"I think there will be a mix of these solutions"*. It requires flexibility, planning, understanding material behavior, project logistics, and institutional dynamics. Interviewees frequently stressed that the success of reuse initiatives depends on early decision-making, ideally during the planning or design phase, and a willingness to challenge conventional linear construction processes.

Three simple and practical approaches have emerged for reusing materials in infrastructure projects. The first approach is to reuse materials internally at the same project site. This includes using excavated soil or crushed rock during construction. The second approach deals with external reuse. This means moving materials between projects. Interviewee 8 mentioned *"the plan is to take it from one site or one building site and straight to the other building site."* The third approach focuses on creating and using reuse hubs. These centralized facilities or platforms store, test, and distribute reusable materials.

4.4.1. Internal Reuse Within Projects

Internal reuse means using materials again in the same construction project. This practice is common in infrastructure projects like roads, railways, and utility networks. During site preparation or demolition, large amounts of materials, such as soil, crushed rock, and other excavated aggregates, are often produced. Instead of moving these materials off-site for disposal and bringing in new ones, they are processed and reused on-site. This practice reduces environmental harm and lowers project costs. A key benefit of internal reuse is that it removes many logistical and regulatory challenges. Since the materials do not leave the project site, the main issues related to ownership transfer, quality certification for external use, and third-party liability are avoided. Interviewee 4 emphasized, *"If you can store the materials within your project, then you control your material balance."* From a cost perspective, internal reuse is a financially attractive option. It removes the expense of buying new materials and disposing of the ones dug up. However, successful internal reuse needs careful planning and coordination in the early stages of a project. Interviewee 9 mentioned, *" The main issue with this type of reuse is storage, and it should be considered during the early design stages."*

Internal reuse practices are to some extent embedded in Swedish public tender processes. The terms 'Case A' and 'Case B' are used. Case A refers to materials that can be reused internally within the project, while Case B refers to surplus materials that are not needed and should be transported outside the project.

4.4.2. Reuse Through Project-to-Project Transfer

This strategy relies on transferring reusable materials from one project to another, usually between sites or within the same public infrastructure authority. This approach increases reuse options beyond the limits of a single project. It becomes useful when internal reuse isn't possible because of challenges related to quantity, timing, or material type. When timelines do not match, the materials must either be stored, incurring additional costs and space requirements, or ultimately be lost to waste streams.

On the other hand, when it comes to lightweight aggregates, the reuse process was facilitated through a closed-loop model in which the material supplier reclaimed, tested, and re-certified their own expanded clay product. Accompanied by an Environmental Product Declaration (EPD), the reused material offered verified quality and environmental performance, which increased client confidence. This case shows a combined approach to outside reuse. Success depends on a well-defined system for certification, traceability, and logistics. This system is often managed directly by the manufacturer, as mentioned by Interviewee 1, *"I think that with the solution of the factories reclaiming components, I think that they will need to feed it into their systems."*

4.4.3. Reuse Hubs

The third and most systemic strategy identified for enabling material reuse in infrastructure projects is the development and use of reuse hubs, centralized or decentralized platforms where used construction materials are collected, stored, tested if needed, and redistributed. These hubs may operate on a municipal, regional, or national scale and can take physical or digital forms. Among the strategies discussed, reuse hubs represent the most institutionalized and scalable approach and the most resource-intensive to implement.

Interviewees recognized that while internal and external reuse strategies offer immediate opportunities, they are often constrained by timing, space, and project coordination issues. Reuse hubs, in contrast, have the potential to bridge these gaps by decoupling supply from immediate demand. Municipalities and infrastructure authorities often have access to land, regulatory leverage, and long-term planning capabilities, making them ideal hosts for such hubs. The interviews showed that when public and private stakeholders collaborate, the viability of reuse hubs increases significantly. Interviewee 10 mentioned, *"It will be necessary with more decentralized hubs to make it work for infrastructure materials."*

A critical dimension of reuse hubs is their ability to manage different types of materials, including both structural components and bulk materials, such as aggregates and excavated masses. Based on the interviews, it is clear that aggregates and masses possess high reuse potential, yet they also present specific logistical and regulatory challenges. Typically, materials generated in large volumes require substantial space for temporary storage and must comply with environmental criteria, such as acceptable contamination levels, before they can be reused.

However, interviewees also pointed out the challenges of setting up hubs. These include the costs of creating storage facilities, developing standard testing protocols, and maintaining traceability through documentation systems. Interviewee 1 mentioned, *"Immediately when you start talking* *reuse hubs for structural elements, the costs of the projects can have a hard time competing with other projects, even if the material cost is very low.*" The most effective reuse hubs will likely be hybrid models that provide physical space for materials while connecting them to searchable digital records that track their origin, specifications, and conditions. Recognizing that these hubs need a clear business model to avoid becoming mere storage sites or junkyards for unused materials is essential. Additionally, success stories from other sectors, like Leca's buyback and re-certification model, show that reuse hubs can work well when supported by industry partners who manage testing and product labeling. Interviewee 1 mentioned *"So the logistics challenge, who will take care of it, who will pick it up, and who will store it, who will assess the quality and sell it, or, transport it further, and, will that actor, market actor or organisation fail in becoming a junkyard and needing to handle lot of waste on their own costs. So that's connected to challenges related to the business model."*

4.5. Materials most suitable for reuse in infrastructure

The analysis of interviews identified excavated materials as the most frequently mentioned and promising category for reuse in infrastructure projects. Excavated materials, such as soil, gravel, sand, and crushed rock, were highlighted by multiple respondents as readily reusable, often reused on-site for filling, landscaping, or sub-base layers. This reuse reduces both environmental impacts and project costs by minimizing the need for virgin materials and transport.

Interviewee 3 explained, *"I truly believe that the biggest opportunity lies in reusing excavated materials."*

Concrete was the second most frequently cited material. Its widespread use in infrastructure and inherent durability make it a significant focus for reuse efforts. Despite its potential, challenges remain due to its varying forms, especially reinforced concrete, which requires careful handling and processing.

Interviewee 1 noted, *"Concrete is durable, as we know, and has good potential for reuse, and it is also associated with a very high climate footprint or environmental footprint."*

Steel was also highlighted as a material well-suited for reuse. Its standardized geometry and ease of refurbishment make it a common choice.

As stated by interviewee 1, *"Steel is very interesting because we have very catalogued or typical geometries very often. We can also follow the history of the element quite easily. Also, the refurbishing process is not as complex as you might think about reinforced concrete."*

Other materials mentioned include wood, particularly structural components that have been protected from moisture, lightweight expanded clay, and composite elements, which show potential for future reuse in infrastructure.

5. Discussion

In the following sections, the study's findings are discussed concerning the research questions that formed the foundation of this investigation. Each research question is revisited and addressed through insights drawn from the empirical data, allowing for a deeper understanding of the opportunities and challenges associated with reuse in infrastructure projects. The thesis aims to design a framework for large-scale contractor companies, which will be discussed during this chapter.

5.1. Barriers to Reuse: A Complex Interplay of Factors

Despite its sustainability benefits, material reuse in infrastructure projects remains largely underutilized due to a multifaceted set of barriers. Both literature and empirical findings from interviews with professionals at Veidekke and other stakeholders underscore that these barriers are not isolated issues but interdependent factors that compound one another. Understanding this complexity is critical to designing practical reuse strategies in infrastructure.

Economic barriers emerged as particularly significant across both the literature and the interview. The interviews highlighted that reused materials often incur higher upfront costs than virgin alternative materials, primarily due to handling, storage, testing, and transportation. This reflects broader literature findings (Aljaber et al., 2023; Firoozi & Firoozi, 2022) that economic concerns, especially a lack of incentives and an immature market, limit the financial feasibility of reuse. The lack of a well-functioning market for reused materials often results in surplus and disposal. This market gap leads to hesitancy in integrating reuse into procurement and planning, particularly when project timelines and budgets are tight.

Quality and technical concerns were also repeatedly emphasized. Interviewers expressed significant challenges in verifying the condition and structural integrity of reused materials. Any uncertainty about load-bearing capacity or contamination poses safety risks for infrastructure components like steel beams or concrete piles. This aligns with research by Tingley & Davison (2011) and Kanyilmaz et al. (2023), highlighting the absence of standardized assessment procedures for reused elements. Some interviewees expressed frustration over the lack of technical data or digital documentation for reused materials. Reuse becomes a liability risk for project stakeholders without clear guidelines or quality assurance.

Regulatory and legal challenges also play a pivotal role in constraining reuse efforts. While the EU and Swedish policies increasingly promote circularity, current building codes and project regulations remain inadequate to handle the variability of reused materials. This misalignment creates a gap between policy intent and practical implementation. As participants described, even when there is a willingness to reuse, the lack of established procedures for certifying the safety and performance of reused materials often leads to their rejection. This reinforces what Firoozi & Firoozi (2022) describe as a structural inflexibility within the regulatory framework, where the rules designed for conventional construction fail to adapt to circular practices.

Logistics and coordination difficulties emerged as particularly difficult in real-world implementation. Several interviewees noted that even when reusable materials are available, coordinating their timely removal, storage, and transport to another site is rarely feasible. These observations resonate with Ding et al. (2023) and Dubois et al. (2019), highlighting that reverse logistics systems common in manufacturing are underdeveloped in construction. Pimentel et al. (2022) also point out that the lack of integrated logistics and material management systems is one of the most persistent barriers to reuse in construction. The lack of centralized storage facilities, shared inventory databases, and reliable tracking systems further complicates reuse, especially when dealing with large-scale components such as steel sections or excavated aggregates.

Knowledge gaps and cultural resistance also represent key barriers. Construction remains a highly conservative industry, often characterized by risk aversion and a preference for conventional methods. Interviewees expressed that many project teams lack awareness of reuse opportunities or consider them too complex or risky. This supports broader critiques that highlight knowledge gaps, limited training, and the absence of reuse-oriented professional norms as significant barriers to adopting circular economy principles in infrastructure (Ericsson et al., 2024; Kummen et al., 2023). Moreover, a lack of internal supporters and insufficient cross-department collaboration were mentioned as obstacles to scaling reuse.

Overall, the findings demonstrate that reusing infrastructure is not just a technical or financial issue but a systemic challenge. Each barrier reinforces the others; unclear regulations exacerbate high costs, quality concerns arise from a lack of logistical infrastructure, and even when solutions are available, they are hindered by knowledge gaps and risk aversion. Addressing these issues in isolation is unlikely to succeed. Rather, an integrated approach is needed that reforms policy, restructures economic incentives, standardizes quality assurance processes, and fosters a culture of reuse within project organizations.

5.2. Enablers of Reuse: Policy, Technology, and Collaboration

The implementation of material reuse in infrastructure projects depends not only on overcoming barriers but also on identifying and actively leveraging the enablers that facilitate this transition. Drawing on interview insights and literature, this section discusses the key factors enabling reuse.

Policy and regulation emerged as the most critical systemic enablers for driving reuse initiatives. Interviewees, particularly those from Trafikverket, RISE, and Region Halland, repeatedly emphasized the need for more proactive governmental intervention. While Sweden already aligns with EU directives such as the Waste Framework Directive (2008/98/EC), many participants stressed that these overarching ambitions must be translated into enforceable, project-level standards. As participants noted, “There is too much room for interpretation in the current legislation; without specific demands in the procurement process, reuse will not happen.”

This sentiment reinforces the role of public procurement as a powerful lever. Public clients like Trafikverket are uniquely positioned to mandate reuse in tender documents, thus setting a market precedent. Literature supports this view, emphasizing that integrating reuse criteria into procurement frameworks is among the most effective mechanisms for accelerating circular practices (Santos et al., 2024; Schützenhofer et al., 2022). When circular requirements are clearly stated, such as minimum reuse percentages or preference for reused components, market actors must innovate to meet these expectations. Moreover, policies can support reuse by clarifying liability issues and standardizing quality assessments. Interviewees highlighted a lack of certified grading systems for reused materials, especially concrete and steel, which limits confidence in their performance and discourages uptake. In this regard, national building codes and environmental regulations could provide more detailed guidance on testing, documentation, and acceptable use cases. For instance, establishing mandatory “reuse-ready” documentation protocols related to environmental product declarations (EPDs) would legitimize reused materials in the eyes of contractors, clients, and insurers. Interviewees also advocated financial incentives such as tax reductions, landfill fees, or material recovery credits. These could help mitigate the cost disadvantages often associated with reused materials. Literature confirms that subsidies, tax benefits, and penalties for disposal have been instrumental in advancing circularity in other sectors (Chen et al., 2022; Gerhardsson et al., 2020).

Another major enabler identified was the role of early design-phase decisions. Interviewees from Veidekke, ReCreate, and other project actors consistently stressed that reuse must be planned from the start. Incorporating principles like Design for Reuse (DfR) and Design for Disassembly (DfD) allows teams to integrate reused components or prepare current ones for future reuse. Participants noted, “If it is not in the design brief, reuse becomes an afterthought; it is too late once construction starts.”

This emphasis aligns with literature advocating for reuse-conscious design frameworks. The “building in layers” concept proposed by Cheshire (2019) and adaptability principles found in CE literature (Geissdoerfer et al., 2017) both support the idea that building flexibility into infrastructure assets can improve material durability and circular performance. However, design integration alone is insufficient without organizational support. Organizational enablers include internal knowledge, training, and access to reuse best practices. Respondents frequently mentioned the absence of practical reuse guidelines and highlighted the need for standardized procedures, such as assessing reused material. Developing internal knowledge databases and offering training on material recovery could significantly enhance organizational capacity to implement reuse.

Digital technologies represent a transformative enabler for reuse by making materials visible, verifiable, and trackable. Interviewees cited BIM, Digital Twins (DTs), and Material Passports (MPs) as technologies with high potential but limited actual use in infrastructure projects. One respondent explained, “We have the tools, but they are not always aligned with project needs or workflows.”

When effectively implemented, digital technologies can provide detailed information about components, including location, condition, and history. BIM and DTs allow teams to simulate the entire lifecycle of infrastructure assets and plan for end-of-life recovery. MPs serve as “digital IDs” for materials, helping stakeholders make informed decisions about reuse. This digital traceability is especially important for infrastructure, where components often remain in service for decades. Literature also highlights AI-driven inspection tools and non-destructive testing methods, like ground-penetrating radar or drone imaging, as crucial for assessing the reuse potential of in-situ components (Çetin et al., 2022; Boldrin et al., 2024). However, adoption remains uneven. Interviewees noted that technologies are rarely integrated into everyday project workflows or procurement platforms, partly due to a lack of training, funding, and standardized digital protocols. Digital marketplaces and reuse platforms were also discussed. Participants recommended coordinated investment into national or regional material banks, integrated with BIM and procurement databases, to facilitate project-to-project transfers and public-private exchanges of materials.

Material reuse also gains traction when environmental and economic benefits are demonstrated. Several interviewees stated that carbon savings and reduced landfill dependency were important motivators, particularly in the context of Sweden’s national climate targets. When reuse could be shown to reduce greenhouse gas emissions or contribute to EPD targets, project stakeholders were more inclined to accept the added complexity. However, the economic case remains mixed. Internal reuse, within the same project, was consistently described as the most financially viable, since it avoids transportation and testing costs. External reuse, involving multiple projects or organizations, was seen as more uncertain due to logistical and quality assurance burdens. This observation is consistent with research that stresses balancing upfront costs with long-term environmental gains (Laefer & Manke, 2008; Kim & Kim, 2020). Particularly, interviewees from LECA and ReCreate highlighted reuse cases that achieved cost parity or savings when properly planned. For example, reused expanded clay aggregates were seen as financially competitive with virgin materials under the right conditions. This reinforces that reuse can be economically viable, but only supported by careful coordination, early integration, and favorable policy conditions.

The role of collaboration emerged as a cornerstone enabler of reuse. Respondents consistently agreed that successful reuse depended on communication and coordination across the entire value chain from public clients and designers to contractors, suppliers, and regulators. Collaboration was especially critical in multi-actor infrastructure projects, with fragmented responsibilities and knowledge. As seen in Project A, collaboration between Veidekke and Trafikverket allowed reuse goals to be embedded early in procurement and design processes. Moreover, the involvement of research organizations like RISE helped validate reused materials and provided technical confidence. These partnerships mirror literature findings emphasizing co-development, shared standards, and trust as key to circular innovation (Knoth et al., 2022; Ikiz Kaya et al., 2021).

Furthermore, collaborative reuse hubs or regional material banks were discussed as promising but underdeveloped. These were considered essential infrastructure for tracking, storing, and reallocating reusable components. Interviewees noted that while digital platforms were emerging, they lacked critical mass and institutional support. Thus, collaboration is necessary for enabling more complex reuse schemes across projects and organizations.

5.3. Feasible Strategies: What Works in Practice?

The choice and success of a reuse strategy rely on several important factors. These factors include the type and amount of material, the project's size and complexity, the regulatory environment, and the availability of storage and logistics support. For example, materials like crushed rock or soil can often be reused directly on-site in road construction projects with slight handling. On the other hand, structural elements such as steel beams or concrete barriers typically need off-site storage, standardized testing, and third-party verification to meet safety standards. Interviews also showed that reuse strategies fall along a risk and value recovery spectrum. Internal reuse is often viewed as the safest option. It avoids many regulatory and logistical problems while providing immediate cost and environmental benefits. In contrast, external reuse adds more complexity because it requires coordination between different projects. However, it can result in better resource use and the recovery of more valuable components.

Despite its advantages, internal reuse is typically limited to materials that are easy to assess, handle, and reapply without major reprocessing. Based on the interview findings, sufficient storage space is crucial for this reuse strategy. This strategy is already used to some extent in Sweden regarding mass balance. The designer identifies the masses and a suitable location for balancing them, which is indicated with a specific note in the tender documentation. For Project A, the designer has implemented this principle by requiring the contractor to reuse materials designated as Case A and transport surplus and contaminated material as Case B. This approach aligns with existing literature emphasizing early-stage design integration to support circular strategies (Iacovidou & Purnell, 2016; Kim & Kim, 2020). However, as the project is still in its initial phase, it remains unclear how accurately the material masses were identified and how efficient the reuse process will ultimately be.

Structural or load-bearing components, which require more extensive testing and quality assurance, are rarely reused internally unless specific expertise or processes are in place. Moreover, the question remains unanswered as to whether the material with specific technical properties can be reused in a load-bearing part of the project, such as for aggregates needed to fill the base or sub-base of a road. This issue requires further research and investigation.

Project-to-project transfer was highlighted as a viable alternative when internal reuse is impossible due to issues like surplus quantity, non-alignment in project timelines, or material types. Participants noted that this strategy can extend reuse options beyond the boundaries of a single project, especially within large public infrastructure organizations. Literature further supports this approach, particularly when supported by shared digital infrastructures, such as material banks or digital marketplaces, to facilitate real-time visibility and material matching across projects (Knoth et al., 2022; Santos et al., 2024). Additionally, tools like material passports, containing detailed data on material origin, composition, and condition, could further support this strategy by increasing trust in the quality and safety of reused materials.

Although reuse hubs offer significant sustainability benefits for infrastructure projects, their potential remains largely untapped due to complex implementation barriers. However, based on the collected data, it is evident that such hubs should be established at the local or municipal level, rather than nationally, due to the inherently transport-intensive nature of infrastructure projects. Localized implementation would better realize the potential of reuse by minimizing logistical constraints and reducing transportation demands. Establishing reuse hubs at a more local scale also increases the likelihood of reusing bulk materials effectively. However, a key challenge identified through interviews is the absence of a viable business model to support the development and profitability of reuse hubs. This highlights the need for future research and in-depth investigation into business model innovation tailored to infrastructure material reuse. In addition, the climate impact associated with transporting materials should be carefully assessed and integrated into reuse planning.

A practical example discussed in the interviews involved the reuse of lightweight expanded clay aggregates. In this case, the material supplier reclaimed, tested, and re-certified the product in a closed-loop model. The reused material, accompanied by an Environmental Product Declaration (EPD), provided verified quality and environmental benefits. This approach, described by Participant 1 as a system where factories reclaim components, illustrates how manufacturers can play a central role in enabling traceable and quality-assured reuse across projects.

5.4. Proposed Framework for Material Reuse in Infrastructure Projects

Building on the findings of this study and the existing literature, this section proposes a comprehensive and actionable framework to support the systematic implementation of material reuse in infrastructure projects. The framework is structured around critical phases in the project lifecycle and addresses design, procurement, logistics, stakeholder coordination, and market development. It aims to translate the circular economy (CE) principles into practical mechanisms tailored for the infrastructure sector.

Early-stage integration within the design and procurement phases is a key starting point in the reuse process. Reuse must not be treated as an afterthought but embedded from the outset of project development. This includes applying design strategies such as Design for Disassembly (DfD) and Design for Reuse (DfR), prioritizing modular construction, flexibility, and easy deconstruction. Such strategies facilitate the extraction of components in a condition suitable for future reuse. The framework emphasizes aligning procurement practices with circular ambitions to enhance this process further. This can be achieved by adopting innovative procurement models, such as circular or performance-based contracts, that reward material efficiency and prioritize suppliers who can provide reused or reusable materials.

Material traceability and documentation play a pivotal role in ensuring the quality and reliability of reused components. Therefore, the proposed framework incorporates material passports and digital documentation systems. These tools allow for systematically registering material characteristics, origin, previous usage, and performance data. By making such information accessible throughout the value chain, decision-makers can evaluate the suitability of reused materials with greater confidence. Quality documentation and third-party assessments should be developed and standardized in tandem, especially for structural materials like steel and concrete, where safety is paramount.

To address the issue of material availability, the framework encourages the development of interconnected material sourcing mechanisms. These include internal reuse pathways within organizations, allowing for component transfer from one project to another, and external reuse networks that leverage regional material hubs or digital marketplaces. Collaboration between stakeholders, both public and private, is essential to support such exchanges. This requires the creation of platforms where designers, contractors, clients, regulators, and reuse businesses can interact and coordinate material supply and demand. Availability of components from other projects, whether within the same organization or externally, should be assessed and actively integrated into project planning.

A well-functioning reuse strategy also requires robust logistics and storage planning. The framework recommends a dedicated logistics plan identifying where and how reusable materials will be stored, transported, and eventually reintegrated into new constructions. Adequate and accessible storage spaces are necessary to maintain the quality of materials during the interim period. Technological tools such as Building Information Modeling (BIM) can track material flows and coordinate timing between deconstruction and new construction phases.

The success of this framework depends significantly on enhancing knowledge and organizational competence. There is a clear need for training and education programs that promote CE principles and equip professionals with the skills to identify reuse opportunities, assess material quality, and implement circular design. The normalization of reuse within organizational practices must be supported by leadership, internal policies, and professional development efforts that make CE an operational norm rather than an experimental practice.

Policy support and regulatory alignment also constitute a foundational pillar of the proposed framework. Guidelines tailored to different material types should be developed to provide technical clarity. In addition, governments and municipalities can support the adoption of reuse through tax incentives, deconstruction mandates, or priority scoring in public procurement for projects with high reuse content. A regulatory framework that supports experimentation and flexible design approval processes for reused materials can reduce uncertainty and unlock innovation.

Finally, the framework calls for developing CE-based business models to sustain reuse practices in the long term. Business models such as material buy-back schemes and reuse as a service for deconstruction and remanufacturing can create new economic opportunities while supporting environmental goals. Encouraging entrepreneurship and market activity around reuse can lead to the emergence of new services, from digital inventory platforms to specialized testing and certification firms. These models are essential to bridge the gap between environmental ambition and commercial viability.

Figures 5.1 and 5.2 illustrate the practical framework, which synthesizes technical, managerial, and economic strategies to operationalize material reuse in infrastructure. It provides a structured pathway for integrating CE into project workflows. It offers actionable steps to address the complex interplay of design, logistics, regulation, and market forces that currently hinder reuse in practice. Implementing such a framework requires cross-sectoral commitment, policy innovation, and cultural change within the construction industry. However, it holds significant potential for transforming how infrastructure is designed, built, and renewed. The framework is grounded in 10 semi-structured interviews with stakeholders and insights from the literature. While these interviews yielded rich qualitative insights, they cannot fully represent the diversity of perspectives across the construction sector. Future research involving a larger and more varied sample would strengthen both the reliability and the generalizability of the findings.

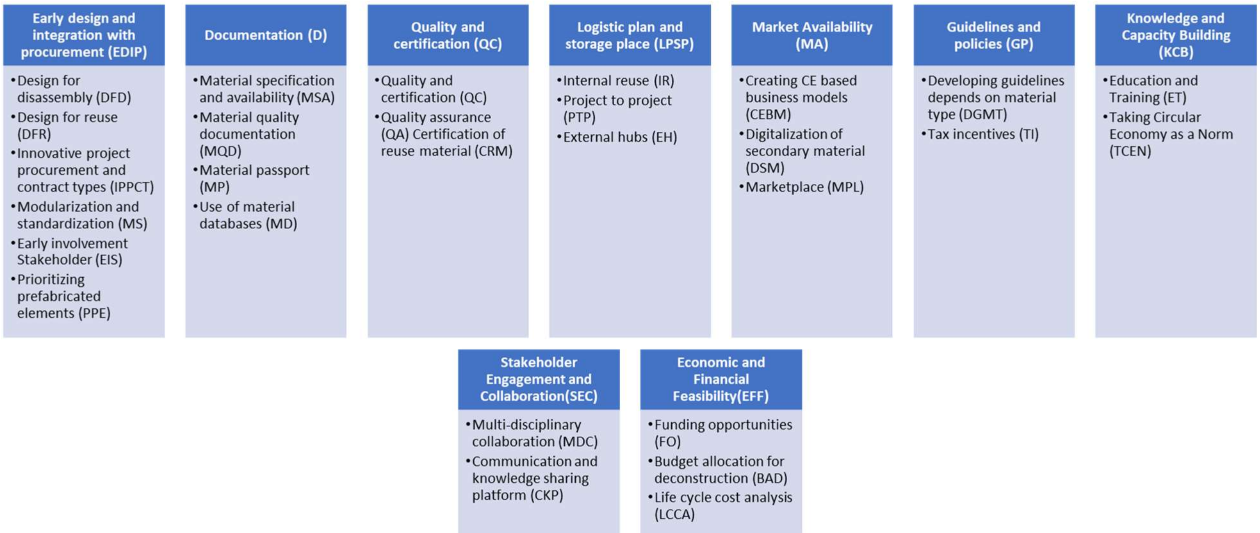


Figure 5.1 List of themes and sub-criteria with their coding

The study synthesised findings from a systematic literature review and thematic analysis of interview data to establish primary categories representing the critical dimensions of material reuse in infrastructure projects. Each category was operationalised through specific sub-criteria derived from both sources, ensuring their practical applicability in project contexts. A combined weighting method (Equation 5.1), integrating empirical evidence from interviews and theoretical emphasis from literature (weighted equally), was employed to determine the relative importance of each category and its sub-criteria. This weighting(see Table 5.1) informed the development of a structured framework designed to support evidence-based prioritisation and decision-making for enhancing material reuse practices.

$$\text{Combined Weight} = 0.5 \times \text{Interview Weight} + 0.5 \times \text{Literature Weight} \quad \text{(Equation 5.1)}$$

The ranking of practical strategies reflects the perceptions and priorities expressed by the interviewed stakeholders, complemented by insights from the literature. It should not be interpreted as a prescriptive, step-by-step guide. Rather, it highlights which measures are perceived as more feasible or impactful within the studied context. Depending on the specific circumstances, different projects may require different starting points or priorities.

Table. 5.1 Lists of the calculated weight of each theme

Theme	Interview References	Interview Weight (%)	Literature Weight	Combined Weight	Rank
Early Design and Integration with Procurement (EDIP)	32	15.09	0.24	0.197	1
Logistics and Storage(LS)	31	14.62	0.11	0.128	2
Guidelines and Policies(GP)	33	15.57	0.10	0.127	3
Market Availability(MA)	28	13.21	0.11	0.121	4
Quality and Certification(QC)	24	11.32	0.10	0.105	5
Economic and Financial Feasibility(EFF)	23	10.85	0.10	0.103	6
Documentation	21	9.91	0.10	0.098	7
Stakeholder Engagement and Collaboration(SEC)	20	9.43	0.09	0.090	8
Knowledge and Capacity Building(KCB)	24	11.32	0.06	0.087	9

Below (see Figure 5.2) is the final framework developed in response to the research question. It consolidates the integrated findings, weighted criteria, and practical sub-components into a structured tool for guiding material reuse in infrastructure projects.

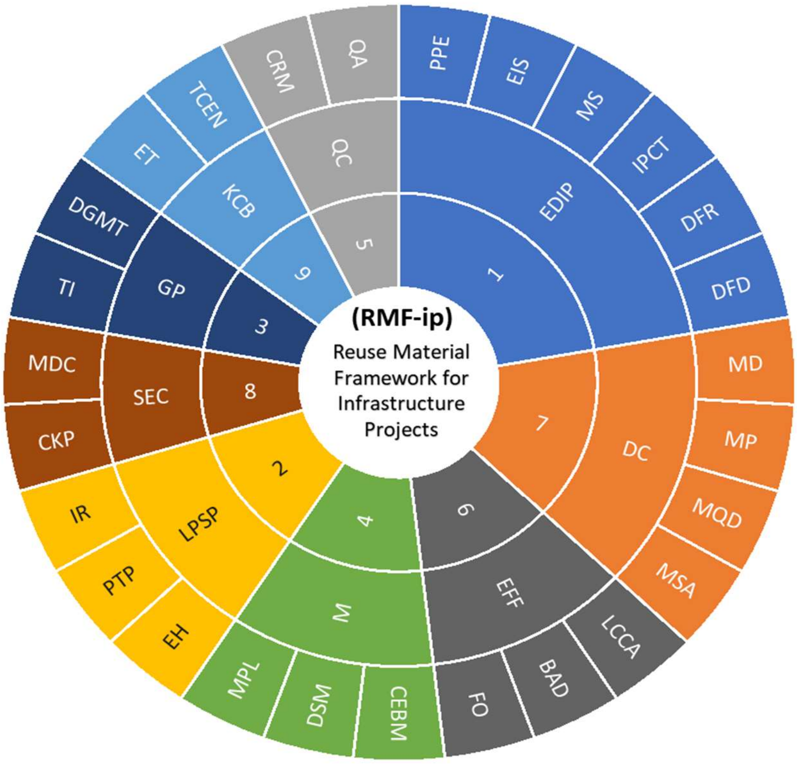


Figure 5.2 Reuse Material Framework for Infrastructure Projects

6. Conclusion

This study has shown that incorporating reuse practices into infrastructure projects holds considerable promise for advancing environmental sustainability, reducing costs, and improving the efficiency of resource use. By extending the lifespan of materials and reducing reliance on virgin resources, reuse can contribute meaningfully to climate mitigation and circular economy objectives. Yet, the findings also reveal a range of barriers that continue to limit widespread adoption.

A central obstacle is the absence of standardised guidelines and regulatory frameworks to ensure the safe and effective reuse of materials. In their absence, stakeholders may perceive significant risks and uncertainties, particularly regarding liability, quality assurance, and compliance. These concerns are compounded by inconsistencies in the quality and availability of reclaimed materials. Cultural and institutional resistance to change further constrains progress, as the construction industry remains strongly rooted in conventional linear practices. Practical challenges, such as material storage, transport, and synchronising supply with demand, also reduce the feasibility of reuse in many contexts.

At the same time, the framework points to clear opportunities and several avenues for enabling greater adoption. Embedding reuse considerations into the design of the project in the early stage is considered crucial. Developing comprehensive material databases could improve traceability and facilitate matching supply with demand. Strengthening collaboration between stakeholders across the value chain would help share knowledge and reduce fragmentation. Targeted investment in research and innovation could address technical uncertainties, while policy incentives, such as tax benefits, grants, and recognition through green certification schemes, could help shift the economic balance in favour of reuse.

Although the path to mainstreaming reuse in infrastructure is complex, the potential environmental and economic gains make the effort both timely and necessary. Achieving this will require coordinated action that integrates policy reform, technological advancement, and cultural change. Such a multi-faceted approach could play a decisive role in unlocking the full potential of reuse and moving the infrastructure sector closer to a truly circular model of development.

6.1. Future Research

Future research could investigate the environmental and economic implications of reuse in different types of infrastructure projects, examining where the greatest benefits might be realised. There may be scope to explore whether standardised quality control methods can be developed and widely accepted, ensuring safety and reliability without creating unnecessary barriers. Pilot projects that incorporate digital tools to track and manage material flows in real time might provide useful insights into their practicality and effectiveness.

Future studies could broaden the empirical base by engaging a wider range of stakeholders and experts, ensuring that the perspectives of policymakers, clients, contractors, suppliers, and designers are better represented.

It would also be valuable to examine the implications of reuse under different contract forms, such as DB, PPP, and DBB. Variations in procurement and governance structures may require adaptations to the proposed framework.

More detailed investigations into specific themes within the framework are needed, particularly circular business models, cost structures, and lifecycle economic benefits. Since reuse lacks standardized practices and its economic outcomes remain uncertain, future research could explore how value can be created and captured in practice.

In addition, studies could investigate how emerging technologies and design methods, such as design for disassembly (DfD), digital twins, and material passports, can be applied to infrastructure projects with very long service lives. Unlike buildings, infrastructure materials are often exposed to outdoor conditions, where weathering and environmental exposure may weaken their performance over time.

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Appendix:

Interview Guide and Study Information

Section 1: Personal questions & interview process

- Can we record the interview for the study?

Section 2: Background

- Please describe your professional background and current role.

Section 3: General questions on reuse

- Do you have a method for determining the reuse potential of a project, particularly in infrastructure?

- Which materials are most suitable for reuse in infrastructure projects?

Section 4: Challenges and barriers to reuse

- Why is reuse less common or nonexistent in infrastructure projects? Do you think financial or logistics is one of the reasons? How/why?

- Have you experienced challenges in managing the reuse of excavated soil or crushed rock in ongoing projects?

Section 5: Enabler of reuse

- What do you think facilitates the reuse of material? Is there an available marketplace for reused infrastructure materials? If so, how accessible and effective is it?

- What are your thoughts on centralized reuse hubs, both on-site and off-site? Have you experienced them in practice? If so, how effective were they?

Section 6: Implementation and development of reuse

- What strategies do you think could be effective for implementing material reuse in current and future projects?

- In your opinion, which types of infrastructure projects (e.g., bridges, roads, tunnels) are most suitable for incorporating reused materials? Do you see a difference between smaller & larger projects?

Section 7: Future potential

- Are there any best practices or success stories you would like to share about your experiences with material reuse?

- How do you imagine the future of material reuse in the construction industry? What changes do you anticipate in the next 5 years or more?

Avsnitt 1: Personliga frågor & intervjuprocess

- Kan vi spela in intervjun för studiens syfte?

Avsnitt 2: Bakgrund

- Beskriv gärna din yrkesbakgrund och nuvarande roll.

Avsnitt 3: Allmänna frågor om återanvändning

- Har ni någon metod för att bedöma återanvändningspotentialen i ett projekt, särskilt inom infrastruktur?
- Vilka material lämpar sig bäst för återanvändning i infrastrukturprojekt?

Avsnitt 4: Utmaningar och hinder för återanvändning

- Varför är återanvändning mindre vanligt eller obefintligt i infrastrukturprojekt? Tror du att ekonomi eller logistik är en del av orsaken? Hur och varför?

- Har du stött på utmaningar i hanteringen av återanvändning av schaktmassor eller krossat berg i pågående projekt?

Avsnitt 5: Möjliggörare för återanvändning

- Vad tror du underlättar återanvändning av material? Finns det en marknadsplats för återanvända infrastrukturmaterial? Om ja, hur tillgänglig och effektiv är den?
- Vad är dina tankar om centraliserade återanvändningshubbar, både på plats och utanför byggplatsen? Har du erfarenhet av sådana i praktiken? I så fall, hur effektiva var de?

Avsnitt 6: Implementering och utveckling av återanvändning

- Vilka strategier tror du kan vara effektiva för att implementera materialåteranvändning i pågående och framtida projekt?
- Enligt din uppfattning, vilka typer av infrastrukturprojekt (t.ex. broar, vägar, tunnlar) är mest lämpade för att inkludera återanvända material? Ser du någon skillnad mellan små och stora projekt?

Avsnitt 7: Framtida potential

- Finns det några goda exempel eller framgångshistorier du vill dela med dig av kring erfarenheter av materialåteranvändning?
- Hur ser du på materialåteranvändningens framtid inom byggbranschen? Vilka förändringar tror du kommer ske inom de närmaste 5 åren eller längre?

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