Potential Circular Strategies for Load-Bearing Building Elements at the End-of-Life

Master’s thesis in Structural engineering and building technology

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

The growing pressure on planetary boundaries, highlighted by the 2023 Stockholm Resilience Centre report shows that six out of nine boundaries have been exceeded. The construction sector, responsible for 39% of global CO2 emissions, plays a pivotal role in this context. This study examines the potential of circular economy strategies to mitigate the environmental impact of multi-residential buildings, focusing on the end-of-life phase and material recovery during demolition. Circular strategies for structural building elements in multi-residential buildings are investigated through a hotspot analysis of life cycle assessments of Swedish multi-residential buildings and a comprehensive literature review. The analysis identifies that structural elements such as floor slabs and load-bearing walls are the major contributors to the buildings' carbon footprints. The work focuses on the circular economy strategies, element reuse and material reuse by evaluating their applicability to different building elements and by identifying practical approaches to enhance circularity within the construction industry, addressing key technical hurdles and proposing viable solutions for sustainable building practices. Element reuse, although requiring repair and reinforcement due to previous life cycle damage, is deemed highly effective. Material reuse is highlighted as a viable alternative for elements like cross-laminated timber and glulam, especially when element reuse is not feasible. Recycling, while common, often results in downcycling, underscoring the need for prioritizing reuse strategies. The analysis indicated varying strategies are appropriate for different elements.

The research identifies significant challenges, including the durability of aged elements, the lack of standardized guidelines, and the complexity of implementing CE strategies for structural elements. Prefabricated elements, such as hollow-core slabs, CLT and Glulam, demonstrate high potential for reuse due to their modular design and ease of recovery. However, in-situ cast elements present greater challenges due to individualized reinforcement layouts and connection areas.

The study concludes that a successful transition to a circular economy in the building sector requires collaborative efforts, detailed technical information, and the development of standards to facilitate the reuse and recycling of structural elements.

Keywords: Structural circularity, Circular strategies, Circular, Element reuse, Material reuse, Load bearing structure, Structural reuse.

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Preface

This thesis is the result of five months of intensive research and marks the culmination of our postgraduate studies in Sustainable Construction at Chalmers University of Technology. Our study aimed to explore the Circular Economy (CE) strategies for the environmental impact of multi-residential buildings, focusing particularly on the end-of-life (EOL) phase and material recovery during demolition.

First, we would like to express our deepest gratitude to our supervisor, Anna, whose expertise, guidance, and unwavering support have been invaluable throughout this project. Her insightful feedback and encouragement have been crucial in shaping the direction and quality of our research.

We would also like to express our sincere appreciation to our examiner, Holger, for his critical insights. His constructive critiques and detailed comments have greatly contributed to the refinement of our thesis.

Furthermore, we are grateful to the professors and faculty members who have contributed to our academic growth. Their lectures, advice, and discussions have broadened our understanding and inspired us to pursue excellence in our research endeavours. In addition, we would like to thank the professionals and industry experts from Plant who shared their knowledge and provided invaluable building datasets and insights into the practical aspects for our hotspot analysis study. Their contributions have enriched our research and ensured its relevance to real-world applications.

We are also thankful to our friends and colleagues for their support and understanding throughout the thesis process. Their encouragement and positivity have been a source of motivation during challenging times.

Finally, we express our heartfelt gratitude to our families for their continuous support and encouragement. Their unwavering belief in us has been our greatest source of strength and inspiration.

It is with immense pride and gratitude that we present this thesis, hoping it contributes meaningfully to the field of sustainable construction and the implementation of Circular Economy principles.

Göteborg March 2024

Chandani Maharjan

Joel André Slunitschek

Abbreviations

BAU	Business as usual approach
BTA	Gross floor area
CDW	Construction and demolition waste
CE	Circular economy
CIP	Cast-in-place concrete
CLT	Cross-laminated timber
DfD	Design for Disassembly
DfR	Design for Reuse
EOL	End-of-life
EOSL	End-of-service life
EWP	Engineered wood products
HCS	Hollow-core slabs
GHG	Greenhouse gases
GWP	Global warming potential
MOE	Modulus of elasticity
MOR	Modulus of rupture / Bending strength
RA	Recycled aggregate
RAC	Recycled aggregate concrete
RMC	Ready-mix concrete

Glossary

Building element
Portion of a construction entity that, by itself or in combination with other such parts, fulfils a characteristic function, e.g. supporting, enclosing, furnishing or servicing building space (Standards Australia Limited, n.d.)

Deconstruction
Refers to the process of taking apart or dismantling a structure, system, or object into its components or elements. This process may involve separating individual components carefully to preserve their integrity for reuse, recycling, or remanufacturing.

Demolition
Demolition is the process of breaking down a building with little or no attempt to recover any of its constituent parts.

1 Introduction

The following section presents the background of circular economy, the aim of the thesis and the investigated research questions.

1.1 Background

The pressure on planetary boundaries is steadily growing at an accelerating rate. In September 2023 an assessment of planetary boundaries was published by the Stockholm Resilience Centre which showed that out of the 9 boundaries, 6 have crossed the threshold (Stockholm Resilience Centre, 2023). There is an increasing need to prioritize sustainability alongside addressing climate change to ensure the continued well-being of humanity. At the 2015 United Nations Climate Change Conference in Paris, 174 countries agreed on a 1.5° Celsius goal to minimize the effects of climate change. To reach this goal, the emission of greenhouse gases (GHG) needs to be reduced drastically to reach net zero emissions for buildings, industries, and several other sectors. Therefore, the European Commission has established an objective to reach climate neutrality for the building sector by 2050 (Directorate-General for Climate Action (European Commission), 2019)

The construction sector is known to be a major contributor to climate change and to exceed several other planetary boundaries. Particularly, the building sector accounts for 39% (IEA, 2023) of the global CO2 emissions of 2022, including 13% embodied emissions from new constructions (One Click LCA, n.d.). Most of the research work indicates that standardized Life Cycle Assessment (LCA) is a valuable tool for assessing different environmental impacts. Although each distinct environmental impact has its importance, the focus is almost always on GHG. Reducing embodied carbon is increasingly being recognised as a crucial focus area to enable effective climate change mitigation in the building industry (Nußholz et al., 2023).

Currently, circular strategies are mostly implemented for minor building components like doors, bathroom fixtures, and windows (Bougrain et al., n.d.). However, these components do not significantly contribute to mitigating greenhouse gas emissions and reducing the environmental footprint (Hradil et al., 2014). Introducing circularity and sustainable circular strategies of major building elements in the construction industry is pivotal to reducing environmental impact. In a time of resource scarcity and perceptible effects of climate change, the construction sector as the largest resource and waste contributor worldwide needs new ways and concepts to tackle climate threats.

1.2 Circular economy in buildings

The concept of circular economy (CE) is different from the current linear take-make-waste economy, in which resources are extracted from the earth, products are made and then disposed of. At the same time, CE is a sustainable system where materials never become waste. It is urgent to adopt circular economy strategies as one of the approaches to change the current linear models and ensure a liveable future.

The Ellen MacArthur Foundation (Ellen MacArthur Foundation, n.d.) bases CE on three design principles:

- Eliminate waste and pollution
- Circulate products and materials (at their highest value)
- Regenerate nature

Circular economy: One of the current sustainable economic models, in which products and materials are designed in such a way that they can be reused, remanufactured, recycled or recovered and thus maintained in the economy for as long as possible, along with the resources of which they are made, and the generation of waste, especially hazardous waste, is avoided or minimised, and greenhouse gas emissions are prevented or reduced, can contribute significantly to sustainable consumption and production

In order to "close the gap" and move towards a circular economy, strategies and potentials for materials, products, and elements in existing buildings need to be explored. This is particularly important in the context of climate change and resource scarcity. Waste management plays a fundamental role in achieving a circular economy, especially in the case of buildings. Waste is generated not only during the construction and demolition phase, but also during the operational phase due to repair works, replacements, and adaptations to the changing needs of the users. Wasting products has negative consequences, including harmful emissions and an increased demand for virgin raw materials to replace the wasted products.

The Waste Framework Directive of the European Union includes a five-step waste hierarchy to prioritize sustainable end-of-life (EOL) scenarios for waste products. Shown in Figure 1, the top priority is preventing waste from arising, which is achievable during the design phase of buildings by creating resource-efficient designs and selecting durable materials. This is followed by reusing, recycling and energy recovery by incineration or similar processes.

*Figure 1. EU waste hierarchy as a foundation for waste management. (*Waste Framework Directive - European Commission, *n.d.)*

The definition for these terms is broad and within the waste directive not specified for the construction sector. Additional frameworks such as the 9R framework (Kirchherr et al., 2017) offer a more detailed description of these Circular Economy strategies within a practical context.

A major issue is the blurred boundaries between the terms, often leading to misinterpretations or unclear intentions for the circularity of the product. Especially for more complex goods like building elements as they consist of multiple components and materials. Multiple papers and sources refer to recycling as the reuse of materials and to reuse as the recycling of products. This ununified use of terms is problematic when analysing suitable strategies for different elements. For these reasons, a tailored CE framework for this research work was developed in chapter 5.

2 Scope

In this chapter, the aim and the respective research questions of the study are described.

2.1 Aim

The study aims to provide an overview of current Circular Economy (CE) practices and explore the potential application of circularity principles to building elements. The primary objective is to highlight the circularity potential of building elements that have the most significant environmental impact. This research is approached from an EOL perspective, within the effects of circular strategies on buildings and the potential of recovering materials during the demolition process are explored. The approach is carried out at the level of individual elements to enable the assessment of circular potential for functional assemblies, rather than solely focusing on the materials within these assemblies. The study showcases circular options for structural building elements and highlights existing tools and methods that support the implementation of circular economy principles. Additionally, the research identifies gaps in current practices and research that need further exploration and discussion.

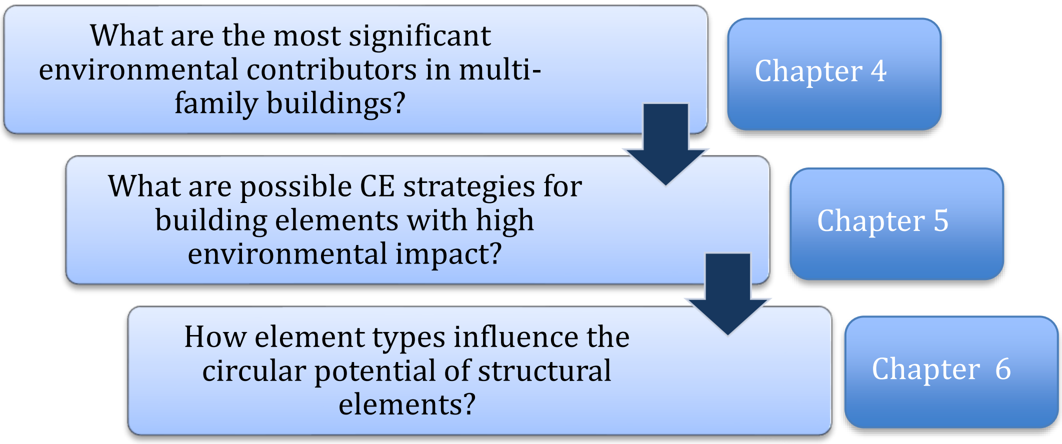
2.2 Limitations

The generalizability of the results is limited by the number of buildings studied in the hotspot analysis. While the included 16 projects provide insights into structural elements of multi-residential buildings in Sweden, the amount is considered too low to be representative of the Swedish building stock. Moreover, the buildings are recent projects and do not necessarily represent older buildings. Given that, building materials and structural systems changed within the last few decades.

The focus of this work is on EOL scenarios and the CE strategies of element reuse, repurposing and remanufacturing. Therefore, emphasis is put on these strategies, while recycling as a CE strategy is only investigated for complementary reasons. Furthermore, the structural elements and the respective CE strategies are researched for technical challenges and possibilities but not for environmental and economic barriers and benefits.

2.3 Research questions

The aim of this study is to find suitable and feasible circular strategies for structural elements. To address this objective, three research questions were formulated as follows:



Chapter 3 will address and answer the first question, primarily focusing on identifying the elements identified through the hotspot analysis. In addressing the second question, the discussion will revolve around circular strategies for elements in Chapter 5. It will explore the potential circular strategies for the identified elements, integrating a new framework derived from the 10 R-principles of circular economy.

Chapter 6 provides a detailed exploration of the third question, covering various material challenges, case studies, and available tools and techniques. It also discusses the circular approaches of the elements, offering insights crucial for drawing conclusions in subsequent chapters.

3 Hotspot analysis

According to the Life Cycle Initiative, a “hotspot analysis is a precursor to developing more detailed and granular sustainability information” (Barthel, 2017, p. 69). The hotspot analysis aims to identify the building elements with the largest impact concerning the carbon footprint of multi-residential buildings. The building elements with the highest global warming potential (GWP) value were further discussed to develop circular strategies.

3.1 Data Input & Methodology

The focus of this study is the GWP impact of structural building elements in multi-residential dwellings in Sweden. The analysed data was provided by Plant (https://www.plant.se/), a software company with knowledge in machine learning, automation, cloud services, construction production, and LCA, based in Stockholm. The study is based on data from the 16 different projects for which LCAs for the life cycle phases A1-A5 have been conducted.

The initial data used for this study is secondary data, compiled and sorted by experts at the company, Plant. The compiled data gathered for this study consisted of LCA results of anonymized 16 multi-residential building projects. Finally, the data was categorized further depending upon the function of the elements, labelled as function type and their corresponding GWP value from phase A1 to A5 (construction phase). The results of the LCAs are given in GWP per total built-up area (BTA) and the respective functional unit was chosen to kgCO2eq/m^{2}BTA. Furthermore, the data collected was processed using Microsoft Excel for sorting and analysing to identify the most critical elements with the highest contribution to GWP. The findings were used to conduct the analysis in subgroups and compare the results to formulate results with graphical illustrations.

Figure 2 illustrates the methodology used for conducting the hotspot analysis, which comprises seven steps. In the initial phase, Plant handled the preparation and selection of data according to the defined scope. The second phase involved gathering, processing, and analysing the data to identify the elements with the highest GWP contributions. After the data analysis, feedback was provided to Plant regarding the study's scope. This feedback included details about the elements, the process of their LCA studies, and additional data required to enhance the quality of the hotspot analysis. This iterative process resulted in the following data scope requested from Plant.

- Multi-residential buildings
- Located in Sweden
- Variability of structural systems
- Variability of element types

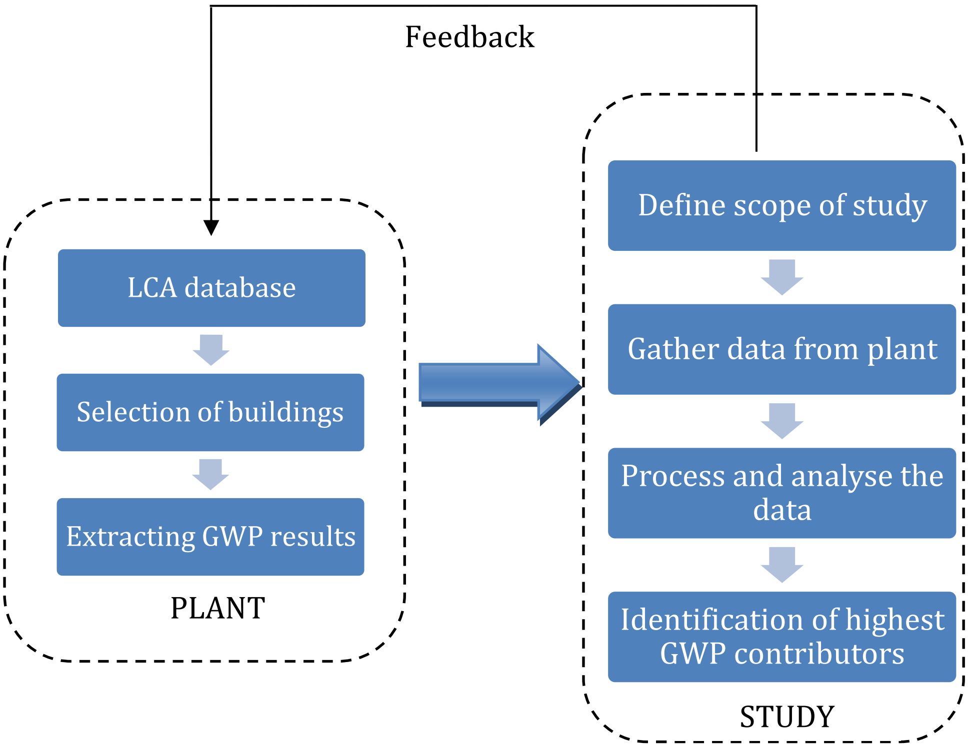


Figure 2. Flow chart showing methodology for hotspot analysis.

Firstly, the data was used to identify the carbon footprint of the different elements of multi-residential buildings. This was then visualized by showing the results in a percentage of contribution through a pie chart as shown in Figure 3. Afterwards, the data was further analysed for the individual elements to study the variation of GWP within each element shown as per the box plot in Figure 4. Lastly, selected elements were sorted to show variations in construction type and the related impact on GWP. This is done for the four major elements for which the circular strategies will be studied in Chapter 6.

3.2 Discussion of Results

The individual structural elements of the 16 projects were compared based on the average numbers for GWP normalized by BTA. The results are depicted in Figure 3 using a pie chart, illustrating the relative impact of the structural building elements on the total GWP of the building. The non-structural category encompasses all remaining elements and components not explicitly specified in the graph. This includes amongst other things non-load-bearing walls, windows, technical systems as well as floor and wall finishes. The study focuses on structural elements and therefore this was not further explored. These non-structural elements account for 30% of the total GWP of an average multi-residential building in Sweden. The remaining 70% is allocated to load-bearing elements, with floor slabs being the most significant contributor, accounting for 33%. This exceeds the impact of non-structural elements. The analysis reveals that individual floor slabs alone are responsible for one-third of the total GWP of multi-residential buildings in Sweden. Examining Figure 4 reveals a wide range of values for floor slabs across the 16 projects. Even after excluding the two outlier points, the numbers for floor slabs vary between 80 and 139 kgCO2eq/m^{2}BTA.

Load-bearing walls contribute to 25% of the total carbon footprint, with 14% attributed to interior walls and 11% to exterior walls. This suggests a slightly higher utilization of interior walls for load transfer in multi-residential buildings. A comparison of these two elements in Figure 4 reveals a divergent distribution of the figures. For interior walls, the middle 50% of the values differ by only 13 kgCO2eq/m^{2}BTA, whereas for exterior walls, this gap widens to 32 kgCO2eq/m^{2}BTA. This wider scattering of numbers could be attributed to the fact that eight different types of exterior walls are observed compared to six types of interior walls.

Additionally, the contribution of the structural groundworks of buildings, including foundation plates and under certain circumstances piles, accounts for 5% and 4% respectively. Given the fact that for foundation plates no material other than reinforced concrete is suitable, these numbers are lower than expected. However, analysing the individual data points reveals that for the majority of the projects, the volume of the foundation plate is significantly smaller than that of elements such as floor slabs and load-bearing exterior and interior walls. Even though these mentioned elements can be constructed with materials of lower environmental impact, the sheer volume increases their contribution to the total GWP of the building. For foundation plates, the range of values is rather small, as differences stem not from material choice but from design and execution efforts. Lastly, columns and beams exhibit the lowest impact among structural elements, with columns at 2% and beams at 1%. Typically, the primary structural system selected for multi-residential buildings does not employ a column-beam system, which can account for the low impact and volume of these elements within the projects.

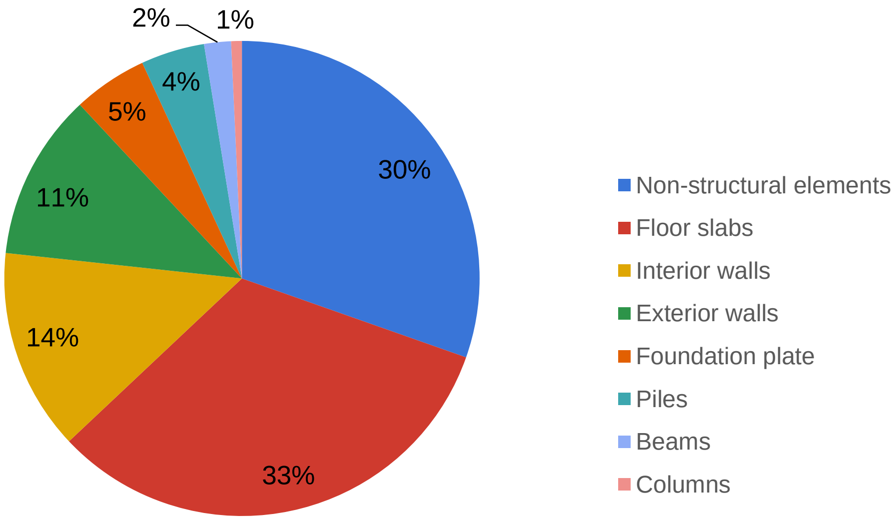


Figure 3. Carbon footprint for elements of multi-residential buildings in Sweden by GWP/BTA for life cycle modules A1-A5. (Own figure)

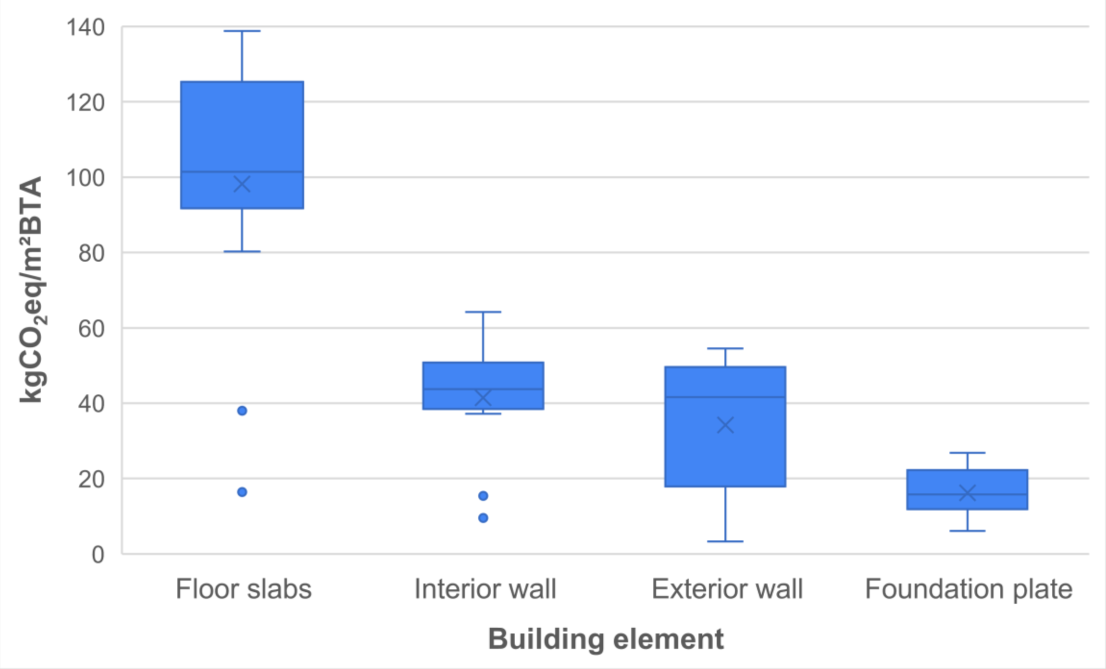


Figure 4. Variation in GWP/BTA for selected building elements. (Own figure)

Element types

The analysis of the overall GWP per BTA of multi-residential buildings, coupled with the distribution of data on individual elements, prompted a more detailed examination of the elements with the highest environmental impact. The dataset included various construction and material types for each element, each exhibiting differing magnitudes of impact in terms of GWP. To prevent the generalization of average figures, the datasets were analysed to investigate the influence of design and material choices. The subsequent chapter will examine the elements in a similar fashion, entailing comparisons between projects to conclude the different systems available for each element.

Floor slabs

The various types of floor slabs in the investigated projects are displayed in Figure 5. Each data point within a category reflects the frequency of that specific type's occurrence in the dataset. Across 16 projects, seven distinct construction types, including combinations of types, have been observed. The predominant floor type observed is the filigree slab, characterized by its thin (approximately 50 mm) prefabricated concrete element with reinforcement installed on top, followed by in-situ concrete to form a semi-monolithic slab. In terms of GWP, filigree slabs demonstrate similar performance across the five projects, typically falling within the mid-range. The remaining construction types show a relatively even distribution across the projects in terms of numerical occurrence. A notable observation is the prevalence of prefabricated elements, with no in-situ casted concrete slabs apart from the filigree slab. The precast slab elements show large impact figures, which presumably are associated with the increased cement content within prefabricated concrete elements.

The lowest impact is notably associated with I-joist wooden beams, with an average value of 98 kgCO2eq/m^2 and ranging between 38 and 16 kgCO2eq/m^2.

However, the data does not specify whether the floor decking is included, or the material used for it. The combination of precast and hollow-core slabs recorded the highest impact, surpassing the average value by at least 34%. These hollow-core slabs were consistently utilized in underground parking garages across all three projects. Due to the larger design load requirements inherent in such applications compared to residential use, these elements may necessitate increased thickness and, under certain conditions, a higher concrete class. These factors will inevitably influence the GWP figure of the element, and it's essential to consider these factors when comparing GWP values. The enhanced environmental performance of lightweight elements is evident in the lower values observed for hollow-core slabs, certain filigree slabs, and I-joist wooden beams. The graph underscores the significantly higher impact of concrete slab elements compared to timber floors. Nevertheless, due to the limited availability of data for timber floor elements, the graph's informative value is somewhat constrained.

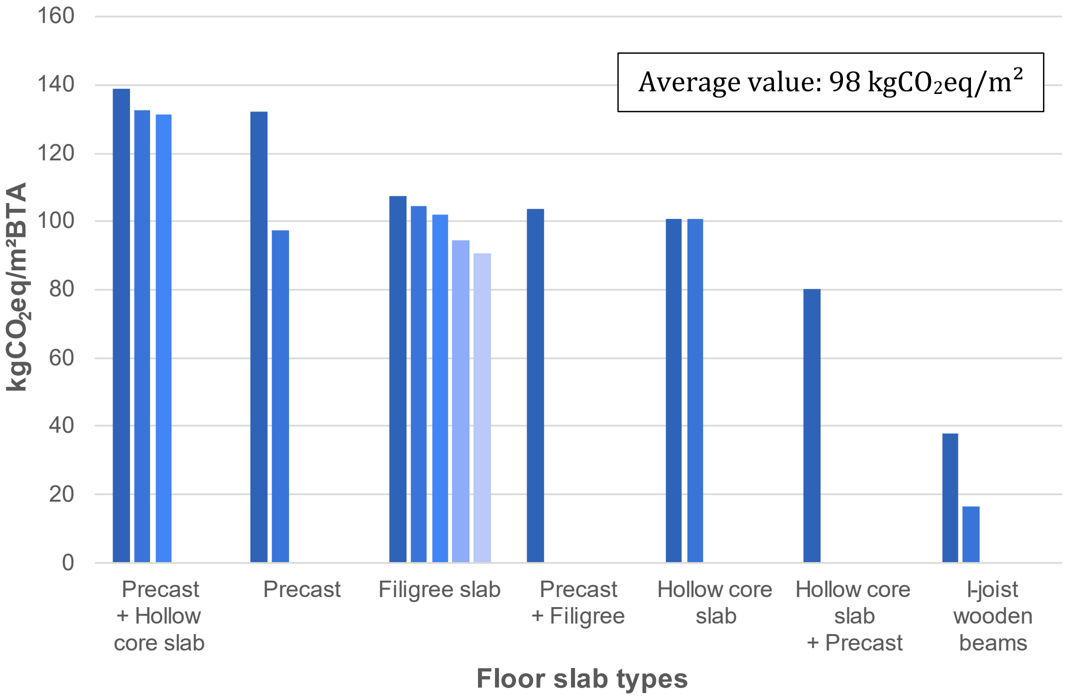


Figure 5. Types of floor slabs in the hotspot analysis and their respective environmental impact. (Own figure)

Interior load-bearing walls

As depicted in Figure 3, load-bearing interior walls contribute to 14% of the total GWP per BTA in Swedish multi-residential buildings, making them the structural element with the second highest impact. Figure 6 displays the various interior wall types identified in the analysed data. Among these, precast walls are the most frequently utilized system representing 50% of the projects. While most of the precast wall systems perform close to the average value, one project exhibits notably better performance, while another demonstrates notably worse performance. The two projects, one performing overall better and the other worse than the average total GWP/BTA, likely owe their differing performance to variations in design effort and pursued environmental goals. Among the systems, Precast + Cast-in-place, Thin-shell precast, and Thin-shell precast + Cast-in-place exhibit similar performance levels, with one project involving thin-shell precast elements demonstrating slightly better performance.

Additionally, it has to be stated that for the projects involving cast-in-place walls as the second element, these walls are located in the basement. The projects featuring lightweight timber walls and the outlier project within the precast category demonstrate the best performances. Notably, the prefabricated walls combined with wooden stud walls are situated in the basement. It would be valuable to determine the proportion of these precast walls to the total GWP of the combined system. However, the data appears to be merged, making it challenging to retrieve this specific information. Similar to the floor slabs, there is minimal variation between the systems except for the wooden stud walls. This suggests that different construction types have a limited impact on the carbon-related performance of structural building elements, with material choice being the predominant factor.

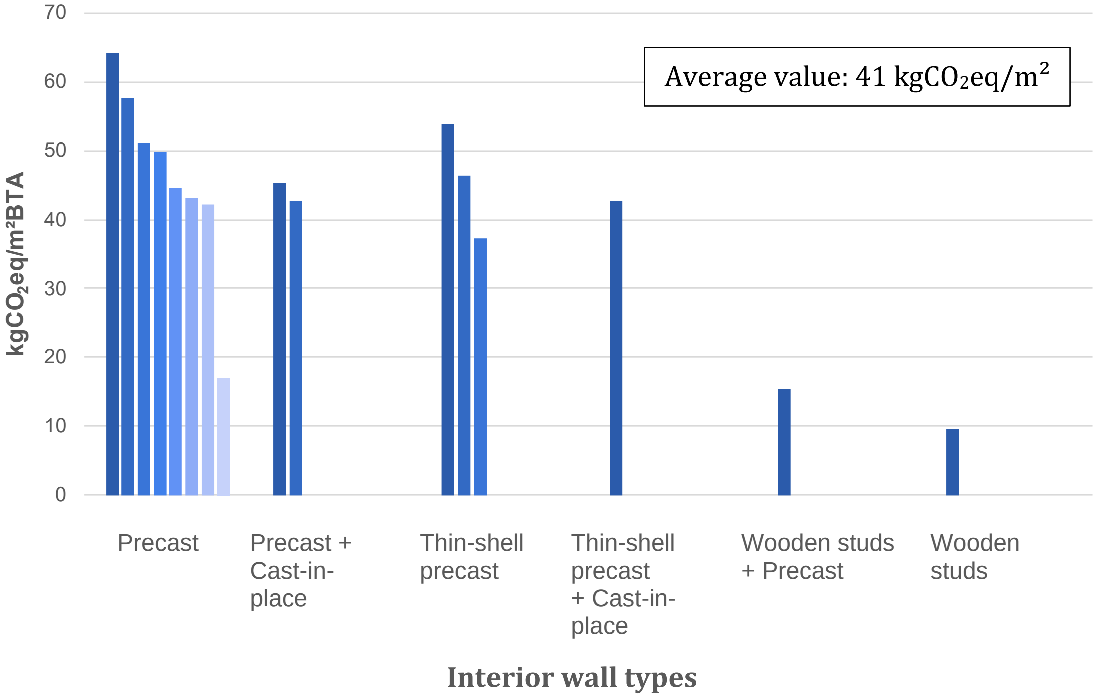


Figure 6. Types of interior load-bearing walls in the hotspot analysis and their respective environmental impact. (Own figure)

Exterior load-bearing walls

Figure 7 displays the various wall types utilized in the analysed projects along with their corresponding values for GWP per BTA. Across exterior walls, eight distinct wall types or combinations thereof have been identified within the dataset. Significant differences in terms of kg CO2eq/m^2 are noticeable between the various systems. Concrete sandwich walls exhibit both the highest impact and the highest frequency of use, closely trailed by concrete half-sandwich walls and combinations thereof. The range of values for sandwich and half-sandwich panels, precast walls, and cast-in-place walls highlights that identical systems can be executed with varying carbon footprints. The lowest figures were attained for timber stud walls and thin-shell panels, either when combined with in-situ walls or used as the sole system. This suggests a reduced GWP impact for lightweight systems.

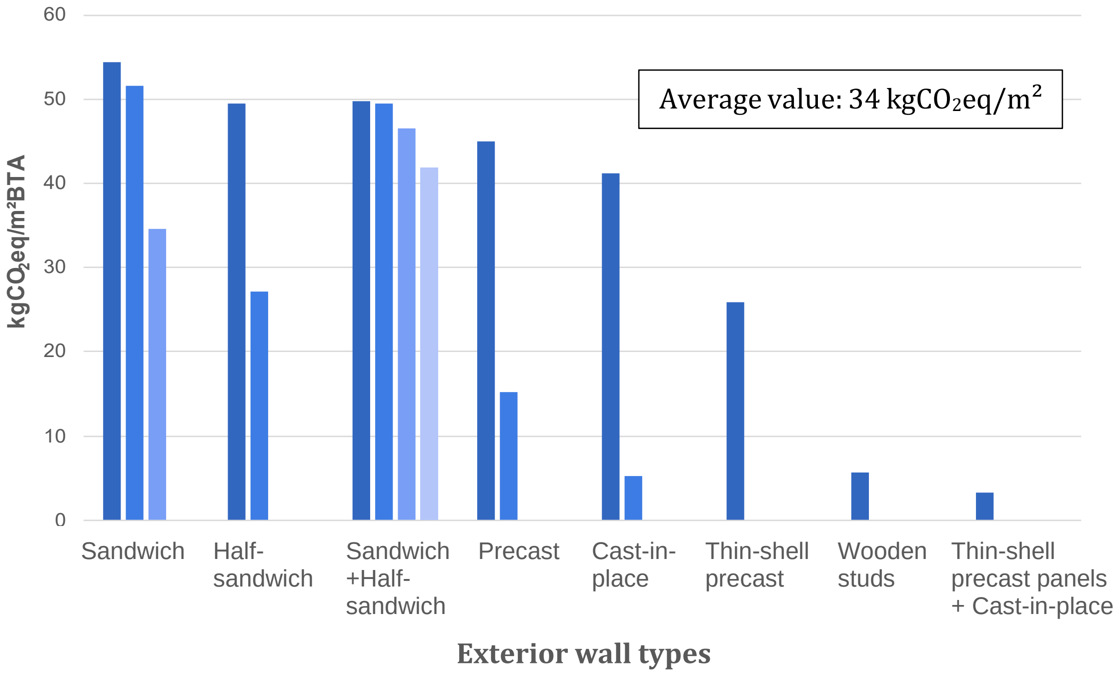


Figure 7. Types of exterior load-bearing walls in the hotspot analysis and their respective environmental impact. (Own figure)

Summary of Findings

Studying the buildings revealed a notably low number of timber and hybrid structures. Both projects incorporating timber stud walls also utilise I-joist timber beam floor slabs. This observation may imply that current practices in multi-residential buildings strongly differentiate between timber and concrete constructions, with less consideration given to hybrid constructions. However, the analysed timber and lightweight concrete systems consistently outperform other construction types in terms of both emissive and embodied carbon. It's important to emphasise that these constructions might require additional materials to meet sound-proofing standards, potentially increasing their carbon footprint and rendering them unsuitable for certain applications.

Regarding the structural concrete elements, a high degree of prefabrication was observed. This will impact the focus of this study to some extent, as it will emphasise prefabricated concrete elements when discussing potential circular strategies for building elements. Furthermore, caution must be exercised in interpreting the informative value of this hotspot analysis due to the limited dataset, focus on the Swedish building stock, and inclusion of recent projects. The observations and associated conclusions may not hold true for older projects or buildings subject to deconstruction in the near future. Analysing the data confirmed certain expectations about building elements and their respective environmental impacts. In-situ and precast concrete elements consistently showed the highest GWP figures, as anticipated. However, some data points were unexpected. The relatively low usage of structural timber, such as CLT or timber frame, was surprising given the growing trend of using timber as an alternative to concrete and steel.

3.3 Limitations

Furthermore, caution must be exercised in interpreting the informative value of this hotspot analysis due to the limited dataset, focus on the Swedish building stock, and inclusion of recent projects. The observations and associated conclusions may not hold true for older projects or buildings subject to deconstruction in the near future. The hotspot analysis was limited to 16 projects due to the restrictions of data publishing rights. Moreover, the data couldn't be presented as individual data points but could only be presented in results as average data.

4 Methodology

The thesis consisted of two parts, the hotspot analysis of life cycle assessment data and a comprehensive literature review, with the latter representing the main part of the report. For the hotspot analysis, the LCAs of multi-residential buildings in Sweden were analysed and the main contributors to the environmental impact of the building were determined. A detailed literature research was conducted for these specific elements to determine the practicability of various CE strategies. Emphasis was put on scientific case studies and pilot projects from the industry. Figure 8 outlines the interaction of the literature research and the LCA analysis and shows the intended outcome of the thesis.

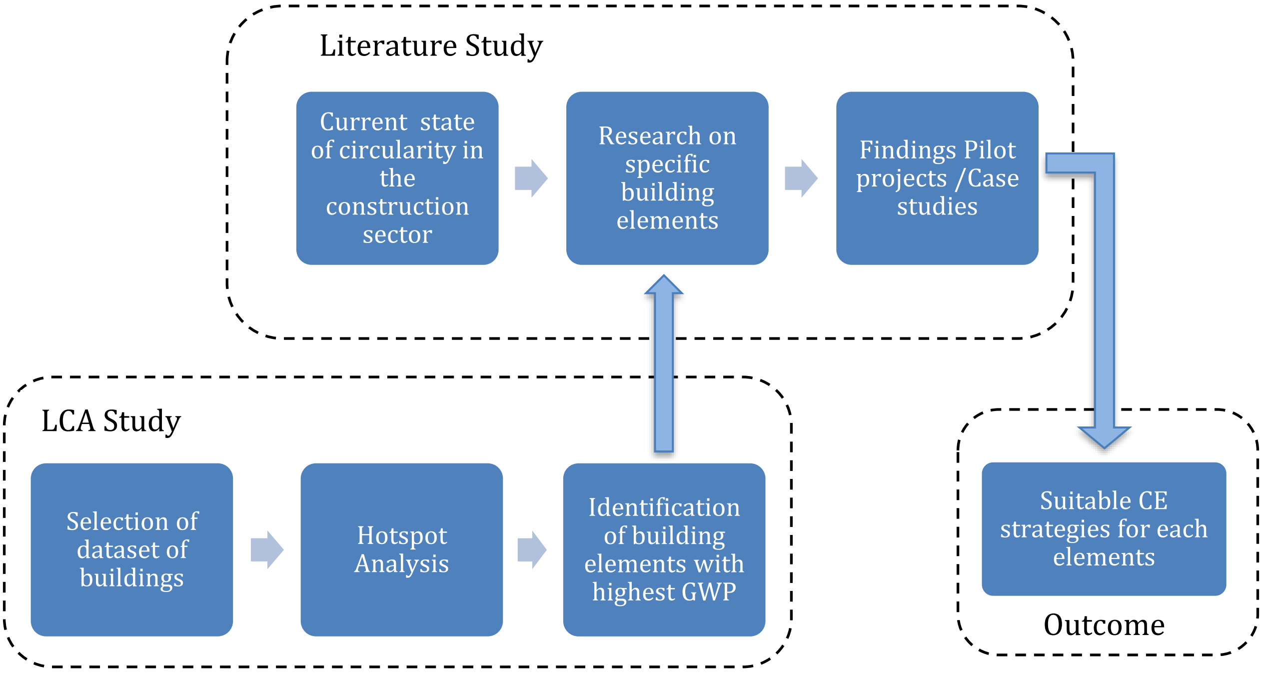


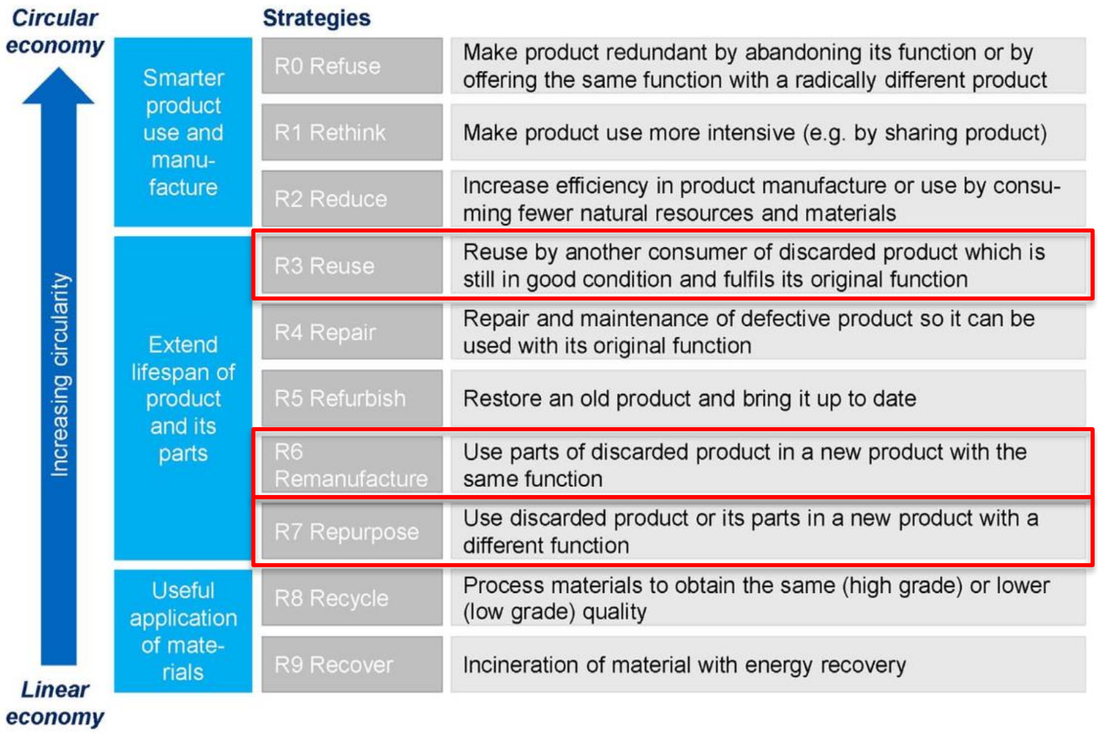
Figure 8. Methodology of the study.

The research began with an examination of circularity within the construction sector. This initial analysis aimed to establish a foundational understanding of the circular economy concept, the current state of circular practices, and their application within the construction industry. In the first phase of the study, a hotspot analysis was conducted on 16 projects to identify the building elements with the greatest contribution to the Global Warming Potential (GWP). This process involved an iterative approach to ensure the inclusion of relevant projects within the study's scope. The outcome of this analysis confirmed the research focus on structural elements and guided the subsequent investigation of specific building elements discussed in Chapter 6.

The second phase of the research involved conducting a thorough literature review. This review aimed to gather pertinent information about the specific elements identified in the hotspot analysis. Examining case studies and pilot projects provided valuable data and insights into circular economy strategies, along with their associated technical challenges and opportunities. Ultimately, the analysis of these case studies and pilot projects informed the discussion and conclusions, allowing for the proposal of potential circular economy strategies for each element.

5 Circular strategies

In the context of building elements, the term "Circular Strategies" refers to alternative approaches for EOSL scenarios, which aim to avoid disposal. To evaluate the circularity of various building elements studied in this research, a framework is necessary. While several CE frameworks exist within industry, academia, and politics, they are rarely tailored specifically for buildings, particularly existing ones. In Figure 9 the 10R framework, one of the most used frameworks within CE, is displayed. The 10 CE strategies, also often called R-principles, are divided into three subcategories: Smarter product use and manufacture, Extend lifespan of product and its parts, Useful application of materials. Potting et al. (2017) indicate the increasing circularity of the principles in ascending order. However, the framework was developed for products in general, and given the complexity of structural building elements, the application might vary for different structural elements. This, along with the limitations of this study, led to a focus on the three red-marked R-principles in Figure 9. These R-principles were chosen because one of the research questions of this study is the extension of product lifespans. Furthermore, R3 Reuse, R6 Remanufacture and R7 Repurpose represent circular actions at the EOL of building elements, while the R4 Repair and R5 Refurbish are mostly applied during the use phase of an element.



	Strategies	
Smarter product use and manu-facture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 Rethink	Make product use more intensive (e.g. by sharing product)
	R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
	R4 Repair	Repair and maintenance of defective product so it can be used with its original function
	R5 Refurbish	Restore an old product and bring it up to date
	R6 Remanufacture	Use parts of discarded product in a new product with the same function
	R7 Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of mate-rials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 Recover	Incineration of material with energy recovery

Figure 9. The 10R framework. Adapted from (Potting et al., 2017)

Also drawing inspiration from the EU waste hierarchy adaption “Delft Ladder” ((Zhang et al., 2022), a concise and suitable framework for this study was developed.

5.1 Business As Usual

The following chapter will provide a brief overview of the status of circularity in the construction sector and present rates for recycling and reuse of the main construction materials. This limitation exists because there is not enough documentation or data available on remanufacturing and repurposing. The term Business As Usual (BAU) refers to the standard practice in the construction industry, which may differ depending on the chosen CE strategies and materials. This study is concentrated on the structural elements, and thus, the BAU will be centred around these elements and the primary materials used for structural systems.

Concrete

Concrete is the most used man-made material globally which comes with both possibilities and challenges. When it comes to building elements like foundation slabs, it's challenging to avoid using concrete because there are no other viable construction materials available for this type of application.

In Figure 10 the recycling rates reveal big differences between the different countries in the EU. The margin ranges from 10% to 95%. For most of the countries, the data from the three different sources vary between 60% and 80%.

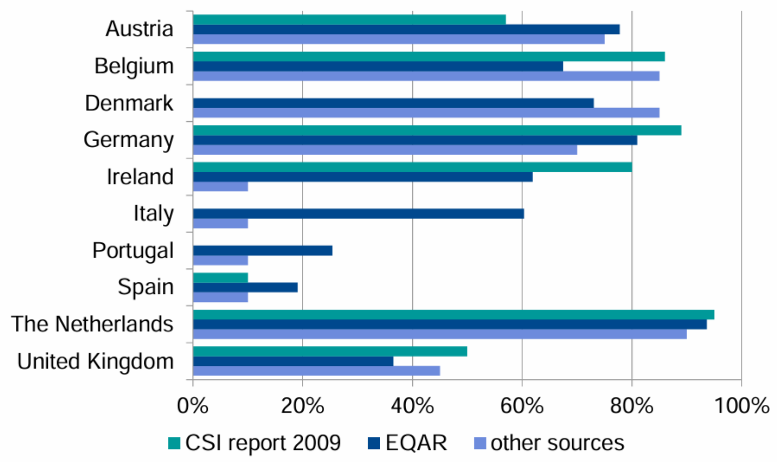


Figure 10. Recycling rates for different countries in Europe. Data from three different sources. (Palm, 2015)

In general, these numbers look promising however it is not further specified if the concrete is recycled into aggregate for newly produced concrete or as road filling to replace other aggregates. In Germany in 2020 19,5% of the recycled concrete was used in asphalt and new concrete, thereby replacing 13,2% of new aggregate. The remaining 80,5% have been used in road construction and other uses (Kreislaufwirtschaft Bau, 2023).
Similar numbers could be found in the Netherlands (Palm, 2015), while in the UK 93% of the recycled aggregates have been used as road fill and only 7% to replace virgin aggregate in newly produced concrete (Sustainable Concrete Forum, 2013). It was not possible to find qualitative numbers for reuse, most likely because the current percentage of reused concrete elements is neglectable.

The primary focus is to maintain materials at the highest possible quality and value for as long as possible. From the data presented, it is evident that while the overall recycling rates for concrete and steel are high, the majority of current circular strategies involve downcycling of these materials and elements.

Steel

In Table 1, the rates for recycling and reuse of structural steel are displayed. While structural steel elements are not the primary focus of this study, the reuse of reinforced concrete elements heavily depends on the condition and integrity of their rebar. Therefore, a brief analysis of structural steel components is conducted. The steel products are divided into three different categories. Firstly, structural sections, covering heavy steel structures like girders and trusses. Secondly, rebar representing the reinforcement steel installed in reinforced concrete. Thirdly, light structural and other construction steel, including purlins and light tube sections.

The figures for recycling, obtained in the USA in the year 2019, show large numbers for structural sections, while for rebar and light structural steel, these numbers are considerably lower. The conductor of the survey did not state the reasons for these deviations, a possible reason could be the higher quality and associated higher value of the heavy steel sections, which encourages the stakeholders to recycle these at enhanced rates. The lower figures for reinforcement steel may be the increased effort needed to separate the concrete and rebar steel but furthermore, that rebar may be regarded as a low-value product.

Table 1. Comparison of steel recycling and reuse rates.
1) (American Iron and Steel Institute & Steel Manufacturers Association, 2021), 2) (Drewniok, 2021)

Product	Recycling 1) [%]	Reuse2) [%]
Structural sections	97	7
Rebar	59	-
Light structural steel, Other construction steel	68	10

Similar numbers can be seen from EPDs for steel products in Germany from the year 2013. For structural sections and rebar, the recycling rate is 88% whereas the reuse is 11% and 1% lost. Meanwhile, for the light structural steel 90%, 0% and 10% are the percentages for recycling, reuse and lost/landfill respectively (Zinke et al., 2016).

Timber

For wooden products used in construction, the available information is much more limited and also less subdivided into products and functions. Therefore, it is not possible to make a qualitative assessment for structural timber elements but for construction wood waste in general. Table 2 shows the data found for the UK and the average data for the EU regarding waste treatment of timber.

While there is a difference between the data for the UK and the EU this is presumed mainly due to the difficulty to assess and trace the treatment of waste wood. More so the division is rather rough and the fact that there are no end-of-waste criteria defined by the EU results in varying assessments within the member states and could explain the differences.

For the reuse rate, no data is available for the EU-27, and the rate for the UK is exceptionally low. According to the source, this category primarily encompasses reuse in the form of planks and boards, but not structural elements. The figures for energy recovery and landfill indicate that a significant amount of wood and timber is still being disposed of and incinerated without undergoing a second life cycle. This percentage is notably high, especially considering that multiple countries in the EU have implemented landfill bans. Overall, the analysis of this data indicates a significant potential for circularity within the timber and construction industry.

Table 2. Data for waste treatment options of construction wood waste for the UK (Astle et al., 2023) and average value for EU-27 member states (European Commission (DG ENV), 2010).

	Recycling into derived timber products	**Reuse**	**Energy recovery**	**Landfill**
UK	20%	3%	17%*	
EU-27	31%	N/A	34%	35%
* Value was stated as unreported in the source. It was assumed that this portion would be landfilled or incinerated for energy recovery.				

5.2 CE framework

Figure 11 shows the developed framework, which includes four CE strategies with additional specifications of the strategy. Given the complexity of building elements and their composition of various components, the framework differentiates between element reuse and material reuse. Element reuse is further divided into onsite and offsite reuse. Additionally, the framework includes recycling, even though this circular economy strategy operates at the material level. Recycling is currently the most commonly implemented CE strategy for building elements and is included for complementary purposes.

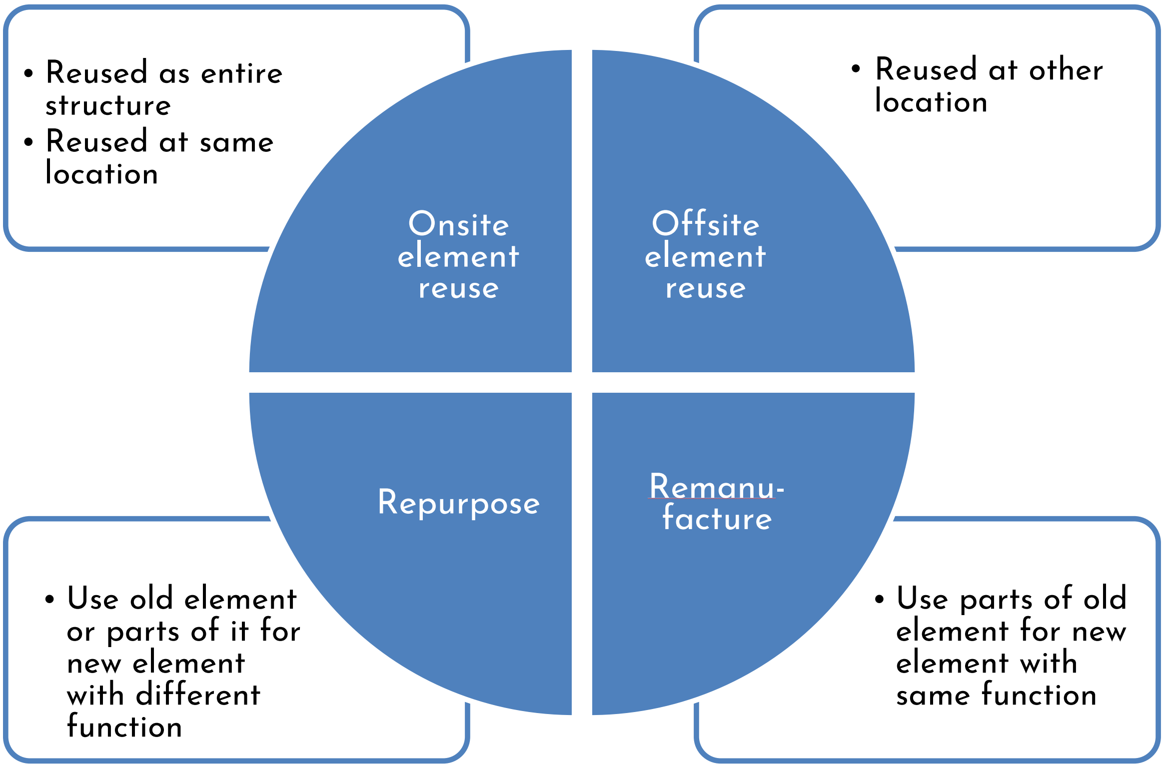


Figure 11. The framework of circular strategies (Own figure).

Building elements are defined by their designed purpose and function rather than their material composition. Hence element reuse specifically means keeping the element in the same function as originally intended. The main aspect is that waste elements are not dismantled into components or materials and are reused on an element level. This, of course, excludes the removal of non-structural elements like boards and finishes.

‘Onsite element reuse’ specifies the elimination of transport and the associated emissions. This includes the reuse of elements without deconstruction of the existing buildings and the reuse on the same site after demounting of the elements.

‘Offsite element reuse’ is the reuse of structural elements in a different location, which includes transportation and possibly temporary storage in a third location. Often needed also for testing procedures.

Repurposing describes the strategy of creating new elements with old elements or parts of it. The new element becomes a different function than the reclaimed elements used to create it. On the other hand, Remanufacturing is creating new elements with the same function as the parts of the reclaimed elements used to create it.

This enables the extended use of elements and components however often leading to a reduced value. It represents an alternative to recycling by avoiding the reprocessing of the elements on a material level.

Within both strategies, the elements can be reutilized in applications with the same, lower, or higher requirements than their original design. Meaning that these elements are equivalent reused, downcycled or upcycled, respectively. This is exemplary shown for concrete elements in Figure 12. In a) the wall and slab elements are reused in the same function as initially. In b) wall and floor pieces are used as parking pavement, as compressive elements while the tensile strength of the reinforcement is devalued in this application.

For c) floor slabs are reused as cantilevers, increasing the stress and load on these elements. Upcycling often requires element reinforcement or combination with additional elements.

Figure 12. Levels of reuse. a) equivalent, b) downcycling, c) upcycling. (Küpfer et al., 2023)

5.3 How to get building elements from donor to receiver building?

The principle of donor and receiver buildings is fundamental in the reuse of building elements within the circular economy framework. The donor building, often slated for demolition or extensive renovation, serves as a source of reusable materials. Identifying a donor building involves a detailed inventory analysis to catalogue potential reusable elements. This process ensures that elements are not only physically retrievable but also meet safety and performance standards for reuse.

Once suitable materials are identified, they undergo non-destructive testing to evaluate their structural integrity. The goal is to ensure that these elements can safely support new loads and comply with current building codes when transferred to a new setting. The receiver building, on the other hand, is the structure where these reclaimed materials will be integrated. This building must be designed or modified to accommodate the reused elements, considering factors such as fit, load-bearing capacity, and aesthetic compatibility.

The transfer from donor to receiver requires meticulous planning to address challenges like transportation, storage, and potential modifications needed to fit the new context. Effective coordination between the project teams of both buildings is essential to align schedules, ensure material compatibility, and streamline the deconstruction and reconstruction processes. Ultimately, the principle of donor and receiver buildings exemplifies a sustainable method of construction, adopting innovation and resource efficiency in the building industry.

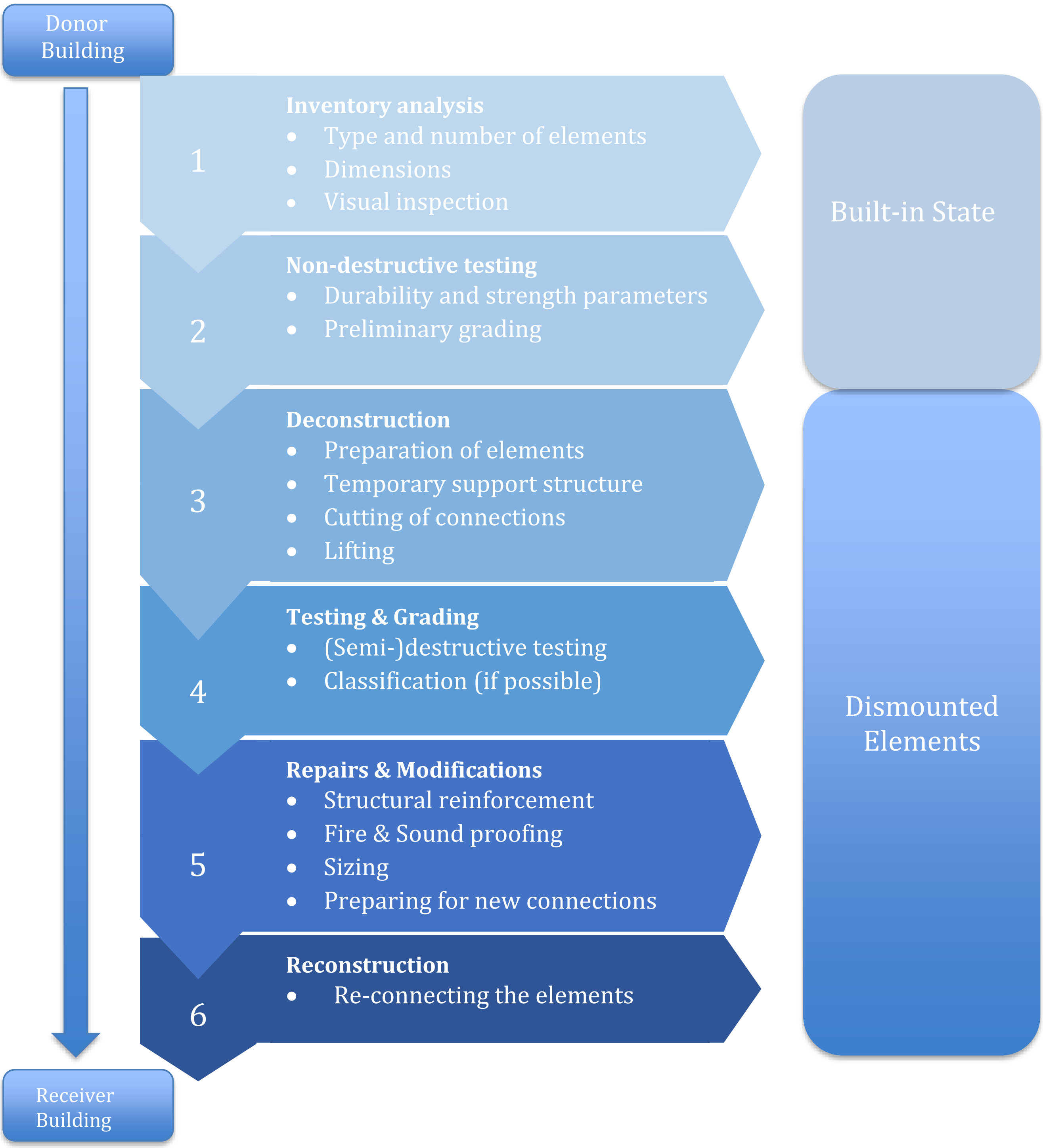


Figure 13. Process from donor to receiver building. (Own figure)

Receiver
Building

Figure 13 outlines the flow of the element from donor to receiver building, involving the six steps. Steps 1 and 2 are done in a built-in state, while steps 3 to 5 are executed on the dismounted elements.

6 Implementation of CE strategies for structural elements

Circular strategies refer to the specific approaches or methods employed to achieve circularity, which involves keeping resources in use for as long as possible, extracting the maximum value from them, and minimizing waste. On the other hand, circular pathways are broader frameworks or routes that outline the journey towards achieving circularity within a particular context or sector. These pathways encompass the combination of strategies, policies, regulations, and initiatives required to transition from a linear economy to a circular one. They often involve multiple stakeholders collaborating across various stages of the value chain to implement circular practices effectively.

This chapter serves as a comprehensive exploration of the circular strategies of structural building elements. This encompasses various stages such as deconstruction, assessment, and testing, as well as reinstallation, along with any relevant standards and guides that may be available. The approach is carried out for a selection of structural building elements determined in chapter 3. The most common construction types of these elements are studied individually, to elaborate on their respective potential circularity. While some methods may be theoretical or have only been developed and tested on a small scale or in laboratory environments, practical implementations and exemplary projects will be provided wherever possible. By addressing the challenges of demolition, implementing effective material testing protocols, and recycling of construction materials, this chapter aims to contribute to the advancement of sustainable construction practices and the transition towards a more resource-efficient built environment. For each element, a table summarizing the discussed case studies and pilot projects is provided in the respective chapter. Additionally, a detailed overview of all case studies and pilot projects can be found in Appendix A.

According to the completed EU H2020 BAMB project and its Reuse Potential tool, the reuse potential of building elements is directly linked to their disassembly potential. Disassembly and reuse potential assess the effort required to dismantle building components without causing damage to the parts themselves or their surroundings. Higher reuse potential results in lower environmental and economic impacts (Durmisevic, 2019). For existing, non-circular-designed buildings this proves to be rather difficult. To deconstruct buildings, which are not designed for disassembly, requires additional time to safely dismantle the rigid connections without damaging the elements. Furthermore, the circular use of structural elements brings several challenges regarding uncertainties of material performance, grading, classification, and reinstallation.

6.1 Material-specific challenges in achieving circularity for structural building elements

Within the construction industry's shift towards sustainability, circular strategies for concrete and timber elements are gaining increasing attention. When it comes to achieving circularity in structural building elements, the challenges we face often stem more from the materials than their specific shapes or forms.

This chapter aims to break down the material-specific issues and opportunities that shape the circularity of structural elements.

For all elements attempted to be recovered the most critical part is the deconstruction process, the majority of damages occur during this phase. The damages can be classified according to G.J. van den Brink (2020) into the following four categories:

- Damage with influence on strength
- Damage with influence on durability
- Damage with influence on sound and fire resistance
- Damage with influence on aesthetic quality

6.1.1 Concrete elements

Concrete is one of the main construction materials today, but at the same time represents a major contributor to the environmental impact of buildings. Furthermore, in some cases, concrete is irreplaceable for specific elements and functions. This underscores the urgency to explore alternative solutions. Characteristics of concrete elements are their high performance, durability, flexibility and in the case of in-situ concrete its monolithic execution. This means that concrete elements are individualised in terms of reinforcement layout and amount. Making it harder to reuse or repurpose since the intended structural requirements need to be equal or the element needs to be downcycled. Table 3 provides a summary of the case studies and pilot projects discussed within this chapter, each labelled with corresponding codes used for reference purposes.

Table 3. Overview of case studies and pilot projects for material-related challenges for concrete.

Code	Details to elements*	Type of building/study	Date	Location	Source
CP1	Pilot project for service life of concrete	Analysis of 40year old elements	2022	Netherlands	(Jilissen, 2023)
CR1	Concrete recycling	University	2021	Switzerland	(Dr. Deuring + Oehninger AG, 2021)
CR2	Concrete recycling	Multi-residential building	2010	Germany	(Knappe, 2010)
CP = Concrete pilot project CR = Concrete recycling project					

Deconstruction

The nature of concrete connections increases the effort and difficulty when demolishing. The deconstruction of existing concrete elements will decrease their dimensions caused by the cutting of the supports. Leading to a decreasing range of possible applications in the reuse process. Standardised demolition processes, specific for the different elements, are necessary to ensure uniform recovery of building elements thus increasing the accuracy of material flow predictions by pre-demolition audits.

Various techniques can be employed for dismantling concrete structures. These include diamond saws, hydro-blasting, and local impact demolition, among others. Of these, diamond saws are the most commonly utilized method (Devènes et al., 2022; Küpfer et al., 2023).
However, a major concern regarding the re-utilisation of CIP elements is the cutting process and the thereby implied change in the statical system. This needs to be investigated more in detail to allow for precise predictions of the mechanical behaviour of reclaimed CIP elements.

Testing

Both durability and mechanical performance are central concerns regarding the reuse of concrete. The durability of concrete means achieving a satisfactory, fully functional behaviour of a structure concerning its load-bearing capacity and serviceability throughout the intended service life. Therefore, reclaimed concrete elements need to be examined to ensure their quality and structural integrity. Testing of mechanical properties, namely compression and tensile strength, as well as an assessment of the chemical condition of the concrete must be conducted for the elements to be reused as structural components. The latter includes tests of carbonation level, chloride ingress and alkali-aggregate reaction. In a pilot project (CP1), Strategic Business Innovation Research (SBIR), of the Dutch Ministry of Infrastructure load bearing reinforced concrete girders from motorway bridges and overpasses were analysed for reuse. Probe from bored cylinders have undergone laboratory tests and the results indicated a very high level of performance with almost zero ingress of aggressive substances over a service life of 40 years. These outcomes were evaluated corresponding to the fib Model Code for Service Life Design (CEB-FIB, 2006) and a remaining service life of 100 years has been predicted (Jilissen, 2023). Several pilot projects and case studies presented in the following element-wise chapters deliver similar results; thereby supporting the fact that concrete structures often have sufficient residual service lifetime. Findings like these play an important role when it comes to the circularity of concrete elements, showing the large gap between the declared and the actual end-of-service life (EOSL). This particular case, featuring elements possessing a higher exposure class than the majority of concrete elements within buildings, clearly demonstrates this issue. Similar observations were made in other projects, in which the concrete still showed high performance and uniform properties (Entra ASA, 2021; Malaga et al., 2023a; Steinar Valbø, 2023).

Geometric and mechanical properties can be evaluated on the deconstruction site before extracting the elements. Non-destructive methods, such as Schmidt rebound hammer and Ground Penetrating Radar (GPR) measurements, provide reliable solutions for identifying these properties.

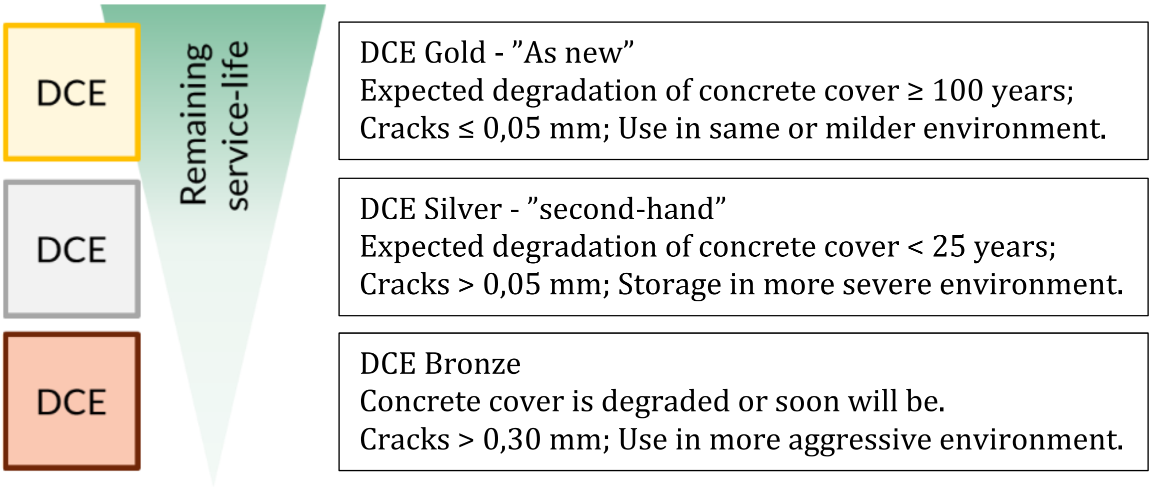
Assessment and grading

Salvaged concrete elements with major damages and signs of use in the form of drillings and holes for installations, which can lower the performance of the element, have to be excluded from element reuse and can only repurposed with restrictions (Malaga et al., 2023a, p. 2). In order to improve the assessment and categorization process of concrete elements, powerful tools are needed.

For the SBIR project, Nebest developed the tool "Reusability scan" (https://www-.nebest.nl/diensten/herbruikbaarheidsscan/) to assess circular options of building elements, considering amongst other aspects general data, structural properties, remaining service life, ease of deconstruction and environmental data. It is structured in three levels, building level to element level to component level, to avoid detailed analysis of elements with low reuse potential. The reusability scan consists of four steps:
1) Archive and file research, 2) visual inspection, 3) residual service life analysis and constructive assessment, 4) verification and monitoring during and after recovery. Numerical tools need to be developed and refined to predict more accurately the residual service life of concrete structures.

Another reusability assessment method will be presented in Chapter 6.3.1 Cast-in-place concrete walls, given that it was developed within a case study for this project. However, it can be transferred to other in-situ concrete elements and therefore may be used for such.

However, predicting the service life is only reasonable when this results in a classification of these reclaimed elements. This is necessary to ensure their quality, increase their value and form confidence in their performance. The Swedish research institute RISE developed such a classification system for the qualitative assessment of disassembled concrete elements, as shown in Figure 14. The system is based on materials tests, a literature review, and a numerical calculation tool to estimate the remaining service life of concrete elements. Analysed elements are categorized into three classes, Gold, Silver, and Bronze. The classification is performed based on these parameters: concrete cover degradation, risk of corrosion, severity of the consequences, crack width and targeted reuse environment. Tested and verified on four pilot studies the system has to be further evolved and expanded to deliver qualitative and reliable outputs (Suchorzewski et al., 2023). The calculation tool, to determine the lifetime expectancy of concrete elements, will be made available at the homepage of RISE (www.ri.se).



DCE Gold - ”As new”
Expected degradation of concrete cover ≥ 100 years;
Cracks ≤ 0,05 mm; Use in same or milder environment.

DCE Silver - ”second-hand”
Expected degradation of concrete cover < 25 years;
Cracks > 0,05 mm; Storage in more severe environment.

DCE Bronze
Concrete cover is degraded or soon will be.
Cracks > 0,30 mm; Use in more aggressive environment.

Figure 14. Classification system "Disassembled Concrete Elements (DCE)" for reclaimed concrete elements. Adapted from (Malaga et al., 2023b; Suchorzewski et al., 2023, Chapter 5).

6.1.1.1 Recycling

The analysis of the current EOL practice for concrete does show promising recycling percentages but as elaborated in Chapter 5.1, the recycled aggregates are mainly used in road construction. While recycling occurs rather independently of building elements, the emphasis in this work is on recycled high-performance concrete for structural applications. Major concerns are within the structural performance of the recycled concrete. The mechanical properties of recycled aggregate concrete (RAC) are influenced by both the quality and quantity of adhered mortar, as well as the replacement percentage of natural aggregates (Pani et al., 2020). Recycled aggregates (RA) exhibit increased water absorption and lower density compared to natural aggregates. Typically, concrete exhibits low permeability, with higher-quality concrete having even lower permeability. Permeability serves as a crucial indicator for assessing the material's ability to prevent liquid loss in structures intended for containing liquids, as well as for evaluating material durability.

Testing

Excessive testing and research must be conducted to increase the ratio of RA in structural concrete. The experimental study of Pani et. al (2020) investigated the effect of parent concrete on the performance of RAC by recycling beams and foundation blocks of an old stadium. Mechanical (compressive strength, modulus of elasticity, and splitting tensile strength) as well as durability properties (water absorption, freeze-thaw, and chloride penetration resistance) were analysed. The results showed that the quality of the parent concrete influences the mechanical behaviour of RAC. The resulting RAC from high-strength parent concrete possessed enhanced mechanical performance compared to RAC from normal- and medium-strength concrete (Pani et al., 2020; Sadagopan et al., 2017). In terms of durability, RAC demonstrated increased water penetration resistance. However, chloride penetration and frost-thaw resistance are reduced, implying the influence of the parent concrete in these parameters. The analysis indicated that the RAC with foundation had a theoretical residual service life 40% higher than that of the RAC with beam (Pani et al., 2020).

While this is only a small sample size and needs further investigation, there is the possibility that structural elements consisting of high-strength concrete are more desirable to recycle when striving for high-performance RAC (Ahmad Bhat, 2021; Sadagopan et al., 2017).

Standards and guides

Within the European Union, there are several standards and regulations regarding the allowed coarse recycled aggregate content in RAC. Table 3 shows the allowed replacement percentage defined by recycled aggregate type and exposure class of the intended function. Type A and B define the aggregate origins. Type A contains ≥ 90% of recycled concrete materials, for type B this is ≥ 70% and the remaining share of ≤ 30% stems from bricks and aerated concrete. The maximum ratio is 50% for exposure class X0, which is limited to interior space applications. To account for the reduced durability of RAC in demanding environments, the following classes are restricted to 30%, 20% and 0% respectively. Figure 15 pictures the application range of RAC depending on exposure and function, according to the Swiss regulations.

Additionally, a technical bulletin (SIA 2030:2021 - Beton mit rezyclierten Gesteinskörnungen) was developed to supplement the existing standards. It contains specified terms, main mechanical properties and technical design criteria (Holcim (Schweiz) AG, 2022).

Table 4. Maximum permitted percentage of replacement of coarse aggregates in RAC (% by mass). (Adapted from (SS-EN 206:2013+A2:2021, 2021)).

Recycled aggregate type	Exposure classes			
	X0	XC1, XC2	XC3, XC4, XF1, XA1, XD1	All other exposure classes
Type A	50%	30%	30%	0%
Type B	50%	20%	0%	0%

However, while the amount of content is regulated, the manufacturing process of RAC and quality control are not specified within the guidelines. Furthermore, the use of RA is limited to coarse aggregates except for the German standard DIN 1045-2:2023-08, which regulates the recycling of fine aggregates. The non-existence of an EU-wide defined end-of-waste criteria for aggregates and concrete represents one of the major restrictions to the industrial-scale recycling of concrete in Europe. National end-of-waste criteria exist, for example in Ireland, but are restricted to non-structural use.

Case studies

Switzerland and especially the city of Zurich is a role model when it comes to using RAC in new constructions. Construction permits demand at least 25% of RA in concrete structures. The RAC is used throughout Switzerland in high-rise constructions. Status from the year 2022 counted around 1200 multi-residential buildings with the sustainability standard Minergie-ECO, with RAC containing over 50% RA (Katerusha et al., 2020; Minergie Schweiz, 2022).

Furthermore, the Minergie-ECO standard requires a maximum transport distance between the recycling plant and the construction site of 25 km. Environmental accounting showed that transport distance has a significant influence on the GWP of recycled concrete (Badraddin et al., 2022). However, the most significant avoided environmental impact is accounted for abiotic material depletion in the form of gravel and avoided land use for landfilling (Holcim (Schweiz) AG, 2010; Knappe, 2010).

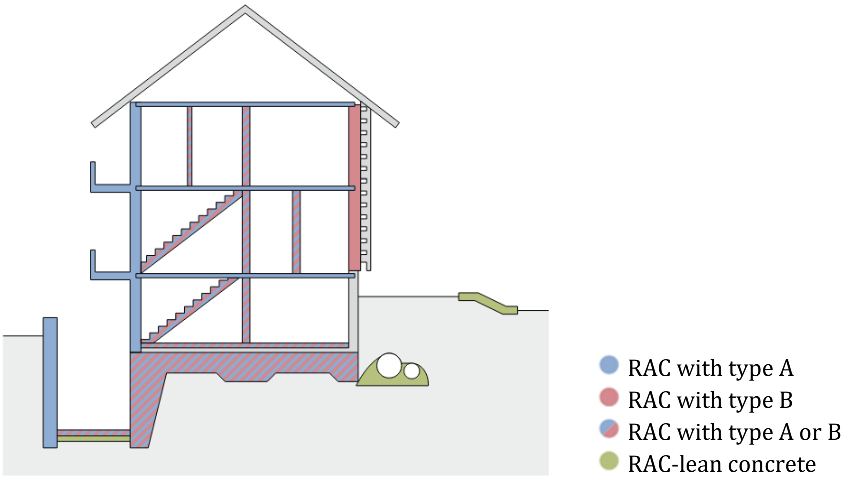


Figure 15. Application areas for RAC after the Swiss model, depending on exposure class and type of used aggregates. (Adapted from (Dr. Deuring + Oehninger AG, 2021, p. 40)).

A lighthouse project (CR1) for the Minergie-ECO standard consists entirely of RAC with grade C30/37 except for the floor slabs as legal regulations prohibit the use of RAC in prestressed structural members. The structural concrete elements in this project contained at least 40% RA (Dr. Deuring + Oehninger AG, 2021). In a multi-residential building (CR2) around 63% RAC in structural quality and function have been used. The recycled concrete was used as load-bearing internal and external walls, floor slabs and in a second building as foundation plate (ifeu-Istitut für Energie- und Umweltforschung Heidelberg GmbH, n.d.; Knappe, 2010). These pilot projects demonstrate significantly that the use of RAC in structural function is technically possible and should pursued within the construction sector to decrease the environmental impact of buildings.

Recycling of concrete gained popularity in recent years to reduce the environmental footprint of buildings. While certain standards exist to regulate and control the manufacturing and application of RAC, so are still gaps to fill, in regulations and research. The most critical knowledge gap is the uncertainty regarding the mechanical performance of recycled concrete elements, especially related to structural elements. Regarding the recycling process, a crucial tool missing is the end-of-waste criteria, to enable a more unified recycling procedure across countries and companies. Results from environmental accounting showed that the ecological benefits of recycled concrete affect land system change, abiotic element depletion and GWP. The latter is rather sensitive to transport distances, which could limit the effectiveness of concrete recycling depending on the location of the project and the local recycling infrastructure.

6.1.2 Timber elements

In many European countries, the use of timber as the main structural material is increasing. Finland plans to build 45% of public buildings of timber by 2025, in Germany the share of timber buildings for residential and non-residential buildings reached around 19% (2019) respectively. In Sweden, 95% of all single-family houses are built using wood and around 11% of multi-residential buildings (Cristescu et al., 2020).

The growing use of engineered wood products, like cross-laminated timber (CLT) and Glulam, in buildings, has led to an increase in demand for wood. While wood is a renewable resource it takes time to regrow trees, especially in a sustainable way. The current EOL practice for building timber products in the EU-27 countries is recycling, energy recovery and landfill each covering roughly one-third of the total waste wood. These strategies represent low circular strategies and landfill which is not desirable in any case.

A popular concept related to the circularity of timber is cascading. The definition of cascading by the EU is: "From a technical perspective the cascading use of wood takes place when wood is processed into a product and this product is used at least once more either for material or energy purposes" (European Commission, 2021). As shown in Figure 16, this approach aims to maximize the utilization of wood resources by sequentially using them in higher-value applications before ultimately being recycled or used for energy generation. By prioritizing products with longer lifespans and higher market value, the cascading chain helps optimize the sustainable management of forest resources and reduce waste in the timber industry. The concept of the cascading use of wood acknowledges that aged timber may not always be suitable for certain applications due to factors such as wear, degradation, or alterations incurred during its previous service life. The subsequent chapter evaluates the factors that impact the circularity of structural timber elements.

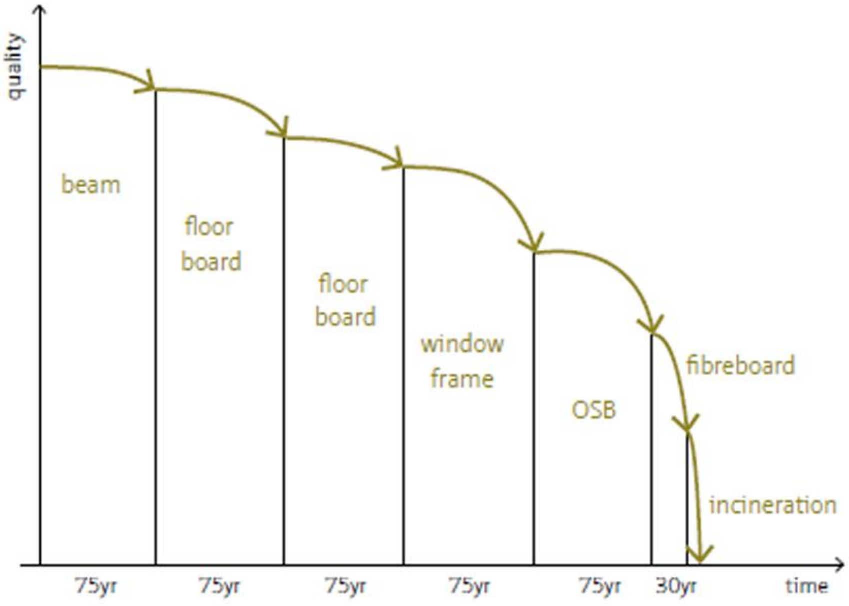


Figure 16. Exemplary cascading of a timber beam. (Cristescu et al., 2020)

Reuse of wood

A key concern regarding the circular usage of aged timber is that wood in contrast to concrete is a natural element and the mechanical properties are harder to control. This in turn makes it more complicated to reutilise, given the higher uncertainty of properties for aged wood. While wooden boards and dimensional timber are to a certain level recycled into chipboards and other downcycled wooden products, the reuse of engineer timber is almost non-existent. One reason that the reuse of structural timber is looked at with caution is the several factors influencing the quality of timber during decades of usage.

These factors involve:

- Weathering (Moisture content, UV-radiation)
- Duration of loading / Age of structure
- Temperature
- Chemical degradation due to preservatives and treatments
- Biological attack (Fungi, Insects)
- Connections like nails and plates

Several studies have been undertaken to gain a better understanding of how and in what magnitude these aspects influence the mechanical properties of timber elements. Reclaimed timber elements from demolished houses in the USA showed 25% lower bending strength and 10% lower stiffness than virgin timber, while timber from industrial buildings showed 10% lower bending strength compared to the design value and 10% higher stiffness (Davis, 2012). These findings agree with Cavalli et al. (2016) which implies that the original quality is of higher importance for the reuse of timber than ageing effects. Most research results state a reduced MOR for secondary timber, primarily caused by the duration of loading (Dong et al., 2024); suggesting that the influence of loading history is significantly higher than ageing effects. Non-destructive measurements of old wooden elements verified no difference in density for new and reclaimed timber (Íñiguez-González et al., 2019).

Currently, the effort to increase the circularity of timber elements in buildings is towards new constructions and innovative design approaches, like DfD and DfR, and therefore element-wise reuse is shifted to the future (Schuster & Geier, 2022). As can also be seen in the BAU data for wood shown in Table 2. This approach then neglects the large amount of timber in the existing building stock. Numbers from the USA from the year 2009 estimate the volume of framing timber in demolished houses to be 4,0x10^{6}m^3 each year, without considering sheeting and finishing materials (Falk et al., 2012). In Japan every three years a 'Survey on actual conditions of construction materials and labor' is held to assess the actual quantity of actual units of building materials in the existing building stock. In the year 2002, Japan's building stock contained 715x10^6 m^{3}of wooden materials, which equals 7 times the annual consumption (Weng & Yashiro, 2003). A case study for southeast Germany from the year 2011 calculated the average wood content in wooden residential buildings to 30 m^3/building. From the total waste wood of residential buildings in Bavaria in 2011, 43% classified as A I and A II (Höglmeier et al., 2017), according to the German Waste Wood Act (German Government, 2002) these timber elements are allowed to be reused or repurposed in a structural function.

Furthermore, the analysis of wooden residential buildings showed that 10% of the structural components are suitable to be reused. This number increases to 16% when considering solid wood which was not used for a structural purpose but has the potential to be (Höglmeier et al., 2017).
These numbers from the industry display the vast potential of the building stock as a valuable timber resource. Moreover, with the gaining popularity of timber buildings in the construction sector these numbers will increase in the coming years.

Impurities

In line with the cascading principle, the EU-funded project CaReWood, standing for Cascading Recovered Wood, explored potential solutions for contaminated wood, currently excluded from reuse in any capacity. Wood contamination can stem from surface pollutants like PVC and heavy metal-based paints, or from preservative ingress within the wood itself. To detect heavy metals, X-ray fluorescence and LIBS (Laser Induced Breakdown Spectroscopy) techniques are employed, while for organic wood preservatives, GC-FAIMS technology (Gas Chromatography-Field Asymmetric Ion Mobility Spectrometry), and near-infrared spectroscopy are viable options. Findings indicate that "if the surface layers are removed a few millimetres deep, that is sufficient. Regardless of the type of wood and regardless of whether wood preservatives, plastics, or paints were used, the wood is then free of unwanted substances" (Fraunhofer-Gesellschaft, 2017, p. 2). Removing the top layers can be achieved through methods such as brushing with rotating brushes, sandblasting, sawing, or planing (Fraunhofer-Gesellschaft, 2017). Eliminating the top layers can be achieved through methods such as brushing with rotating brushes, sandblasting, sawing, or planing (Fraunhofer-Gesellschaft, 2017). By employing these detection and removal techniques, it becomes possible to upcycle salvaged timber components, enhancing their circular potential. Timber elements previously deemed contaminated and thus unsuitable for reuse as elements or materials may now be granted a second chance at life.

Grading

A primary challenge in the reuse of structural timber is the absence of a grading system and CE certification for reclaimed timber, leading to a lack of confidence in the structural elements. Strength for new sawn timber is done by the standard EN 14081-1:2019 and the current strength grading for timber is done by property prediction based on the whole population basis. This approach is not applicable to recovered wood for the following reasons (Sandberg et al., 2022):

- Species and growth areas need to be known. Which is often hardly achievable for recovered wood.
- Knowledge of original grading and sorting process needed. Mostly impossible due to lack of documentation.
- Extensive destructive testing is needed for this grading system. Testing facilities are expensive and oftentimes insufficient selection of the same kind of reclaimed timber.

The application of Visual Strength Grading (VSG) standards to recovered wood resulted in high rejection rates, as reported by several authors (Arriaga et al., 2021; Davis, 2012; Íñiguez-González et al., 2019).
Primarily attributed to the presence of warps and wanes although their impact on mechanical properties is minimal (Esteban et al., 2010; Llana, Íñiguez-González, et al., 2023; Martitegui et al., 2007). This aligns with the outcomes derived from examinations conducted on rafters and beams sourced from a historical roof assembly, as reported by Krofl (2019) at the University of Ljubljana. The outcomes of the non-destructive testing are depicted in Figure 17, illustrating a significant contrast in rejection rates.
While visual grading consistently yielded a rejection rate of over 55%, this decreased to approximately 5% when employing the longitudinal frequency method for measurement. Furthermore, there was an increase in the attained strength class across all instances upon evaluation of the dynamic modulus of elasticity (dMOE).

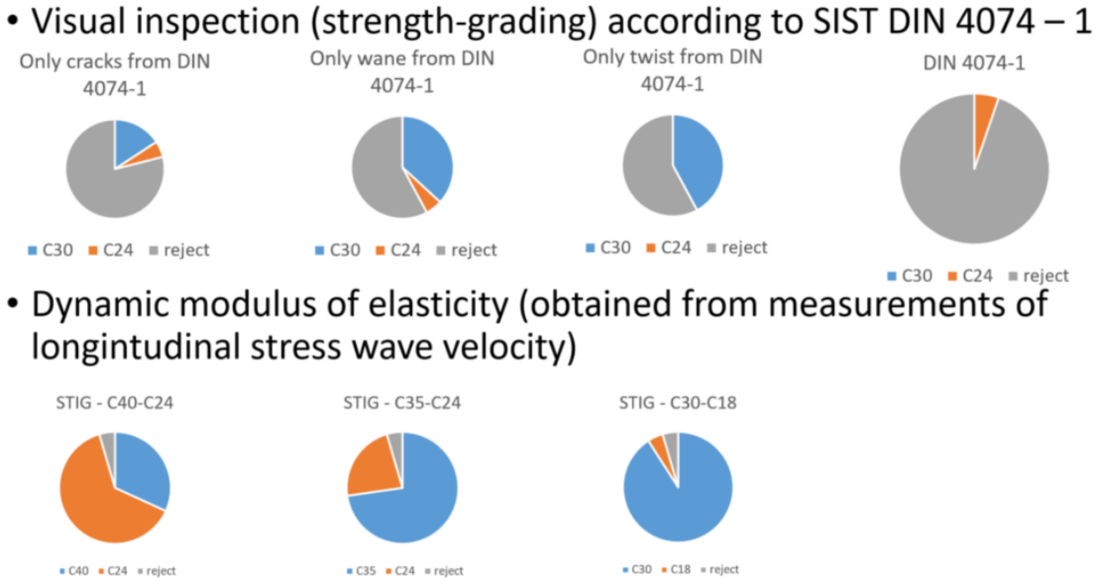


Figure 17. Non-destructive testing of wooden rafters and beams in Slovenia (Krofl, 2019).

Within work package 5 “Properties of Recovered Wood” of the InFutUReWood project (*InFutUReWood*, n.d.) a new grading approach, see Figure 18, for recovered wood was suggested. The introduced grading system is based on a probabilistic piece-by-piece approach that enables the determination of the characteristic design values to be done for a limited set of timber, for example, a set of timber boards used in a specific building. The authors however admit that the alternative grading system will have a lower certainty regarding the material properties compared to the current grading system and suggest to counteract this by more conservative design values (Sandberg et al., 2022).

Furthermore, recovered timber needs also be examined for damages during service life and for modifications done during the construction or demolition. Therefore, additional grading criteria will be necessary to account for these issues, like the number and magnitude of cut holes and notches, in-service decay, mechanical damage, and chemical treatments.

Mechanical damages constitute the most critical issue. Fractures or cracks may not be visually detectable once the load is removed (Sandberg et al., 2022).

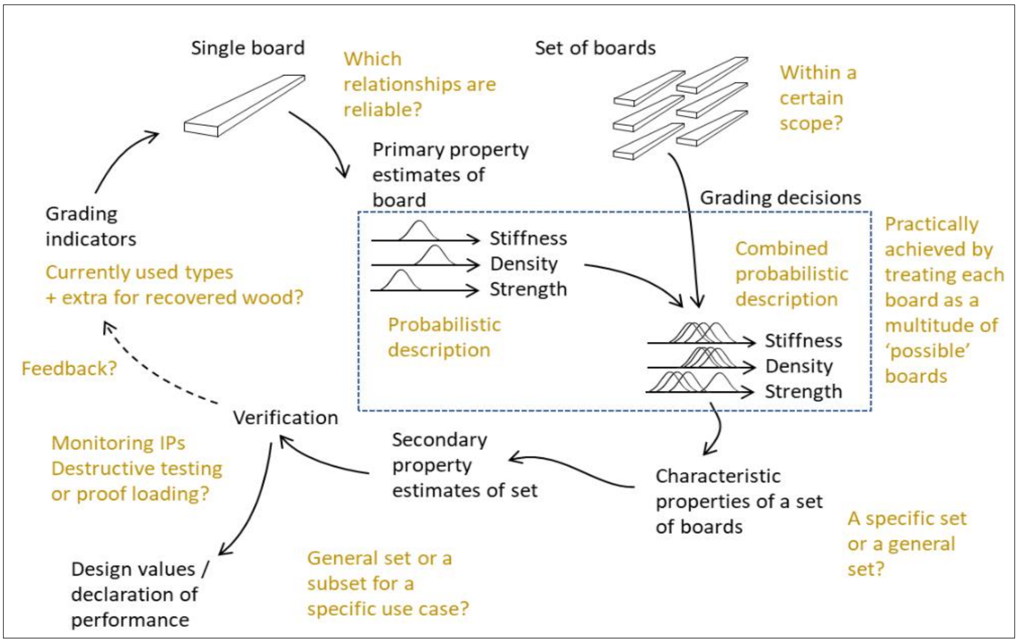


Figure 18. Outline of the alternative grading system (Sandberg et al., 2022).

Connections

Timber elements, especially CLT and glulam often use connection techniques like finger joints to increase the length of the element. Even more so when using secondary timber which is not unified in length and width. Therefore, it is essential to verify that these connections do not pose a structural weak point. The tests from Dong et al. (2024) showed that none of the CLST elements failed at the finger joints but rather due to the existence of knots and delamination. Concluding can be said that finger joints made from low-grade secondary timber did not influence the bending stiffness of the CLST elements. The tested CLST elements satisfy the bending stiffness and strength specifications of ANSI/APA standards (APA, 2024; Dong et al., 2024). Most often used in modern timber structures is the dowel-type connection, which is mainly dependent on the embedment strength. Tests according to EN 383:2007 were conducted on recovered spruce and oak specimens, with the result that recovered wood performed comparable to new timber and thereby according to Eurocode 5 (Uí Chúláin et al., 2021).

All these factors increase the difficulty of element reuse for structural timber from existing buildings which is also visible in the very limited number of case studies to be found. As at this time reuse of full-size timber elements comes with major challenges, alternatives are explored by the reuse of materials in the form of repurposing and remanufacturing, often referred to as secondary timber as well as material recycling.

Assessment guides & standards

The reclamation and circular use of structural timber elements involve multiple steps including grading and testing. The various outcomes define the potential circular pathway of the elements.

A decision tree for this procedure is comprehensively summarized in Figure 19, leading to element reuse, material reuse or recycling.

In Norway, two standards regarding the evaluation of reclaimed timber have been released in 2024 with a third part in planning (*New Standards for the Evaluation of Reclaimed Wood | Wood Technology*, 2024).

- NS 3691-1 Evaluation of reclaimed wood - Part 1: Terminology and general rules
- NS 3691-2 Evaluation of reclaimed wood - Part 2: Impurities
- Part 3: Visual strength sorting (In process)

The content includes investigation, treatment, and general requirements of recovered timber, either for reuse or recycling.

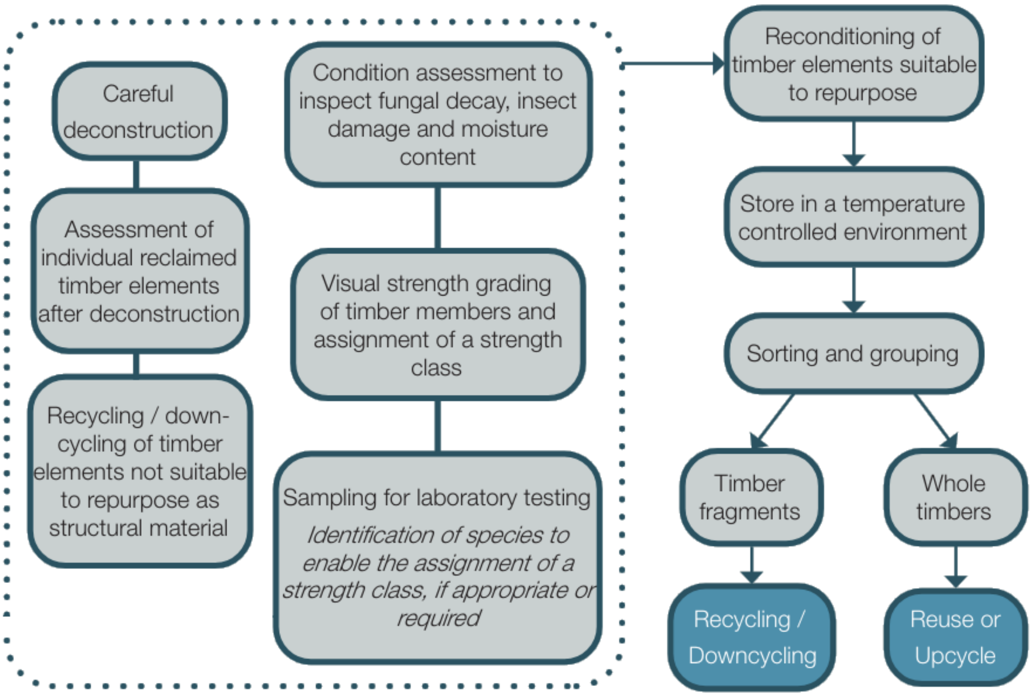


Figure 19. Reclamation management and decision tree for structural timber elements. (Adapted from (Godina, 2022))

6.1.2.1 Recycling

As evident from Table 2 recycling of timber is already practised in the construction industry, to a certain extent at least. However, it mainly involves non-structural components. The current primary applications for recycled wood include particleboard manufacturing, animal bedding, and landscape uses.

One of the main hindrances in the process of timber recycling is the presence of impurities within the wood, such as metals or traces of wood treatments. Metal parts can potentially damage the recycling machines, while the chemicals used in the previous wood treatment are undesirable in the wood chips mix during the recycling process. Moreover, they can reduce the mechanical performance of recycled timber (Xie et al., 2013). The Norwegian standard NS 3691-2:2023 defines multiple categories and requirements for wood chips from recycled timber. It distinguishes between three different categories as stated in Table 5. These categories for impurity are necessary to group the resulting chips before reproduction, ensuring the quality of the wooden chips regarding size, moisture and colour (Höglmeier et al., 2017).

According to case studies in Germany, approximately 44% of wood from demolition and construction waste can be recycled into OSB and particleboards (Höglmeier et al., 2017).

Table 5. Categories for impurities and the respective requirements.

Category	Requirement
Pure	There should be no traces of the impurity.
Partially pure	Some traces of impurities may be present.
Impure / not assessed	The material has mixed impurities.

Although it is currently technically impossible to recycle timber into primary structural elements such as beams and CLT, it is still possible to use it as a secondary structure. The cascading chain for wood designates floorboards and window frames as the next valuable options. However, when considering the cascading chain within the framework of circular strategies, recycling initiates with the production of oriented strand boards (OSB) from reclaimed timber. OSBs serve as secondary structural components, employed as floor and roof sheathing, as well as webs for wooden I-joist beams (APA – The Engineered Wood Association, n.d.).

It can be concluded that recycling wood in structural elements is more difficult than recycling concrete. This is because primary structural elements like beams and CLT, which consist of planks, are made of sawn solid wood rather than processed material. When wood is recycled into chips, strands, and particles, the quality of the wood decreases, making its use in these applications unfeasible. Therefore, recycling of timber should only be considered for wooden elements that cannot be reused or remanufactured. The reason for prioritizing wood recycling should not be based on the increased effort required for sorting during demolition.

6.2 Floor slab

As indicated by the hotspot analysis, floor slabs contribute to 33% of the total GWP of an average Swedish multi-residential building. These floor slabs function not only as structural elements but also as installation planes, sound insulation, and horizontal partitioning. This multifunctionality imposes greater demands on both new and reclaimed elements. This is particularly significant considering that reclaimed floor slabs were designed decades ago, and regulations concerning fire safety, soundproofing, and durability have evolved since then. Hence, these factors must be considered when considering the reutilization of floor slabs. This chapter will investigate four different types of floor slabs: cast-in-place, hollow-core slabs, cross-laminated timber, and glulam. While glulam is not used as a floor slab directly, it is commonly used as a load-carrying system and is often combined with the other investigated slab types. For this reason, it will be included in this study. Each of the floor constructions will be explored for available circular options and their technical feasibility, existing assessment methods and available classification systems.

Table 6. Overview of case studies and pilot projects involving floor slabs.

Code	Details to elements*	Type of project	Building type	Date
CIP1F	Cast-in-place concrete	Inventory analysis	Office building	2022
CIP2F	In-situ concrete	Onsite reuse	Multi-residential building to single-family house	2019
CIP3F	In-situ concrete	Remanufacture	Parking pavement	2021
CIP4F	In-situ concrete	Remanufacturing	Storage building	2022
CIP5F	Cast-in-place walls	Repurposing	Basement wall to footbridge prototype	2021
HCS1	Hollow-core slabs	Offsite reuse	Office building	2021
HCS2	Hollow-core slabs	Onsite reuse	Parking garage to office building	2021
HCS3	Hollow-core slabs	Inventory analysis	Office and warehouse	2021
HCS4	Hollow-core slabs	Inventory analysis	Office building	asm. 2021
HCS5	Hollow-core slabs	Offsite reuse	Warehouse to residential building	2024
HCS6	Hollow-core slabs	Offsite reuse	Multi-residential to office building	2023
CLT1F	CLT floor panels,	Inventory analysis, LCA study	-	2022
CLT2	CLT panels	Remanufacturing, Lab study	-	2024
CLT3	CLT panels	Remanufacturing, Lab study	-	2023
CLT4	CLT panels	Remanufacturing, Lab study	-	2023
CLT5	CLT panels	Remanufacturing, Lab study	-	2018
CLT6	CLT panels	Remanufacturing, Lab study	-	2021
G1	Glulam beams	Inventory analysis, LCA study		2022
G2	Glulam timber frame	Offsite reuse	Ice rink hall	2019
G3	Glulam	Onsite reuse	Office building	1996

G4	Glulam timber frame	Reuse, Laboratory study	Textile factory	2023
G5	Glulam timber frame	Onsite reuse	Industrial hall	2024
CIP = Cast-in-place HCS = Hollow-core slabs CLT = Cross-laminated timber G = Glulam			F = Floor slab (addition to distinguish between floor and wall elements made from the same material) *Only structural elements are mentioned.	

6.2.1 Cast-in-place concrete

Cast-in-place (CIP) concrete floor slabs represent a common construction type in existing multi-residential buildings, represented in the hotspot analysis CIP in the form of filigree slabs. While the construction type includes a prefabricated element, most of a filigree slab is executed in CIP. The prefabricated element is mainly used as lost formwork, to ease the production process. The hotspot analysis showed that CIP floor slabs have a somewhat higher impact than hollow-core slabs and a significantly higher impact than wooden floors.

In-situ concrete elements differ in several crucial aspects from precast elements. Its monolithic nature, no defined connection and individualised production. As mentioned, even filigree slabs, which are installed as precast elements, are connected by in-situ cast concrete on top. This fact increases the complexity and difficulty of the deconstruction and recovery of these elements. For this reason, the circularity of CIP floor slabs is currently focused on recycling.

Deconstruction

The possibilities of elements to be used in any form after their EOL are strongly dependent on their initial design, connections, and condition after dismantling. During the deconstruction of buildings for the recovery of cast-in-place concrete floor slabs, two aspects need to be prioritized. The recovery of single slab elements from a monolithic poured slab and the structural safety of the donor building (Noordhoek, 2022). For the recovery of monolithic concrete floor slabs, the methodology in Figure 20 can be used. Divided into three stages, each possibly conducted by different contractors, it considers the analysis of the targeted elements and assessing their reuse potential, the demolition and transportation as well as the implementation in the new construction. Thereby considering a possible third life cycle of the element by trying to find easy demountable connections, respecting the principles of DfD and DfR. In Figure 21 the steps of the deconstruction phase are shown. After securing the element and the surroundings, the slab is then cut with, for example, a diamond saw or a jackhammer. For the lifting of the elements, different techniques are possible. As shown in Figure 21 c.) installing anchors in the slab to attach cables or as described in Figure 28 wrapping a steel mesh around the element.

For the research stage, two separate tools are used: the reusability scan and the possible tool. The first tool is the Reusability Scan, described more in detail in chapter 6.1.1. This is used to identify possible elements for reuse.

The second tool called the 'Possible Tool', was developed by Thijs Noordhoek (TU Delft) and verifies if the element can be used in commercial residential constructions as well as predicting the avoided environmental impacts and necessary investment costs for planned reuse. In the presented step-by-step guide, the tool is used twice. First, as preliminary estimation to assess which elements are worth quality check and material testing. Secondly, after obtaining valuable material data the tool can then more accurately predict the reuse potential of the analysed elements. These elements can be either approved for reuse or rejected. If rejected, alternative circular options such as repurposing or recycling can be explored.
This tool can be accessed via web application by the following link: https://mybinder.org/v2/gh/Thijsn99/monoo/HEAD?urlpath=%2Fvoila%2Frender%2Fmonovoila.ipynb

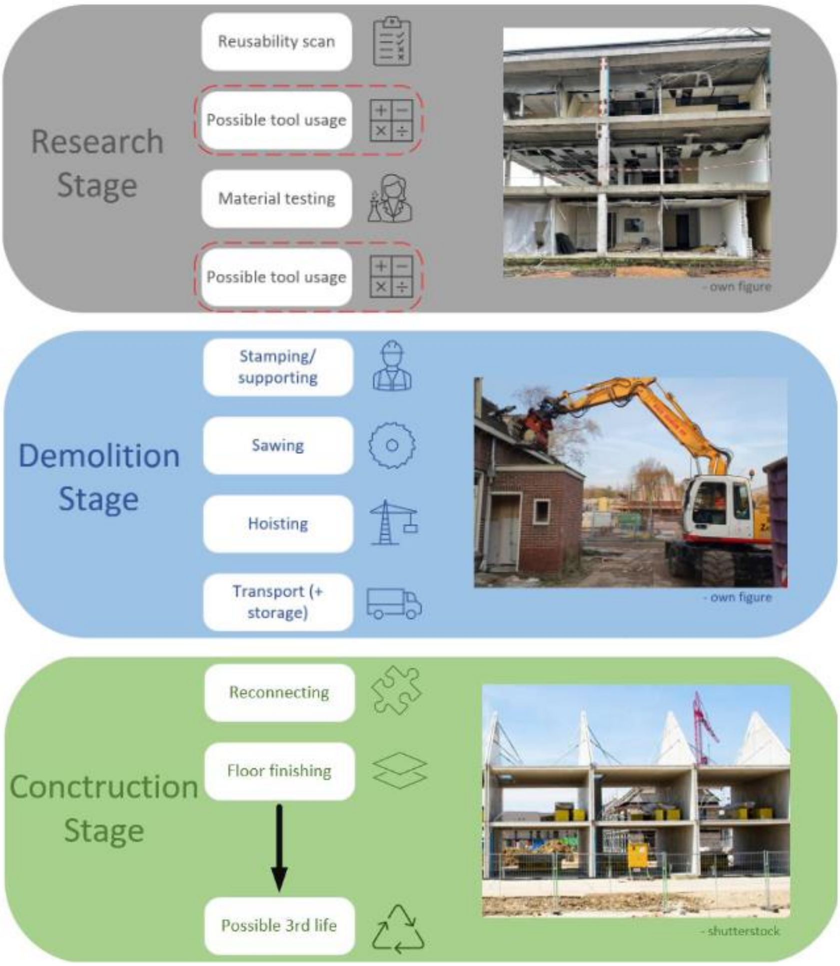


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Figure 20. Step-by-step guide for the reuse of monolithic concrete floor slabs. (Noordhoek, 2022)

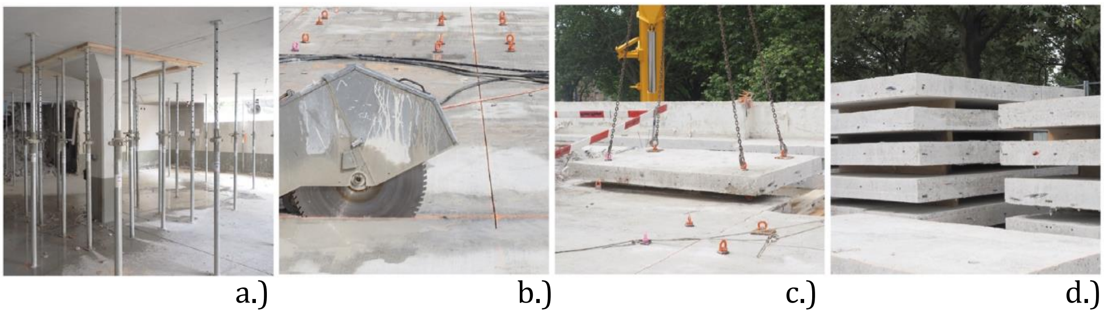


Figure 21. Processes in the demolition stage. From left to right: Stamping, Sawing, Hoisting, Storage. (Küpfer et al., 2024)

Contradictory to hollow-core slabs, in-situ casted elements pose problems when disassembling due to reinforcement spreading over the entire slab construction. While for hollow core slabs, the load transfer from plate to plate occurs through the connections between the elements, only these have to be demolished which limits the deconstruction effort.

Whereas for in-situ slabs, if divided into elements for cut-out, the reinforcement runs across multiple elements and thereby increases the difficulty.

Taking this into account, Figure 22 presents a possible sawing pattern for in-situ floor slabs. The dimensions of the proposed elements geometry represent the most common spans for the intended future use, in this case, residential buildings in the Netherlands. Rather than maximizing the yield the recovery of the elements was focused on the reuse application.

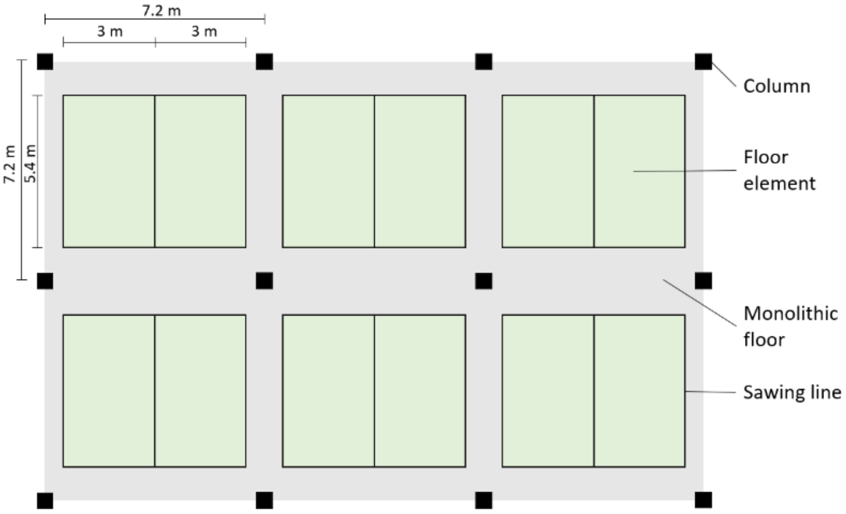


Figure 22. Possible sawing pattern for cast-in-place concrete slab. (Noordhoek, 2022)

Connections

When reclaimed slab elements are used as primary or secondary floor elements, the reconnection of the elements differs. For the primary structure, the two sections on the left in Figure 23, the reclaimed element is fixed by a steel angle to the wall and two elements are connected by a mortar joint and a steel plate on the top. When used as a secondary structure, two sections on the right, the reused elements are rested on a supporting girder.

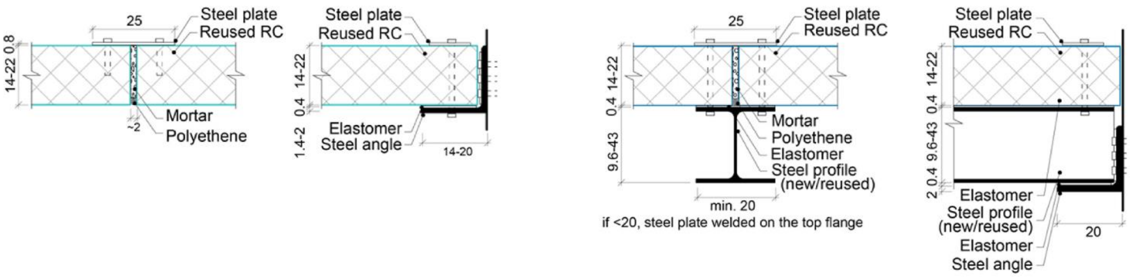


Figure 23. Longitudinal and transversal sections of connection details. For primary (left) and secondary structure (right). (Küpfer et al., 2024)

In Figure 23 a steel profile was used as a supporting girder but Figure 24 shows an alternative connection with a concrete shallow beam. This one-way slab connection was developed by Volkov (2019) by creating U-voids in the second-hand slabs, installing connection bars, and then grouting the voids with low-shrinkage concrete. In connection with a shallow beam, this approach could replicate the initial slab load-bearing system. This exemplary visual representation was done for filigree slabs, but the approach could be adapted for in-situ casted slabs.

The load transfer between the two slab elements is achieved with a connection bar spanning from element to element whilst passing through the beam.

Both variants could be realized with reclaimed elements for the supporting girder as well, to increase the circularity of the entire construction. When combining reused concrete slabs and reused steel girder a maximal GWP reduction of 94% was achieved, compared to conventional practice (Küpfer et al., 2024).

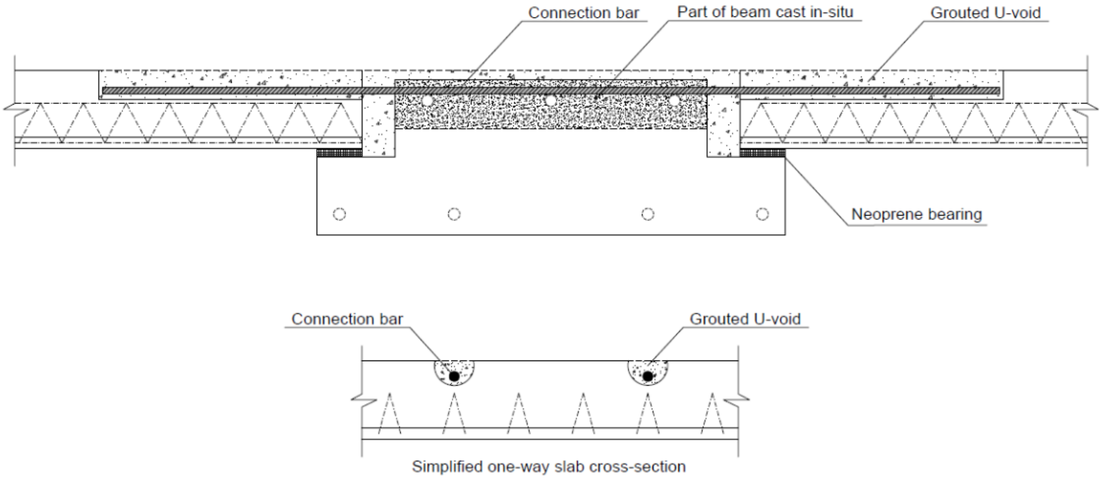


Figure 24. Cross sections of proposed connection for in-situ floor slabs. (Volkov, 2019)

Case studies

The existing methods for reusing reinforced concrete (RC) pieces extracted from CIP structures are limited to two primary design approaches. The first uses blocklike elements predominantly in compression in the new construction. So used a case study in Switzerland (CIP3F), amongst other elements, in-situ floor slabs to build a parking pavement of 233 m². The reclaimed elements were placed in a predefined layout, optimised for available element sizes to minimize the cut-off waste of these elements. The elements were then connected by various joint-filling materials, depending on the different zoning and exposure.

The second design approach uses larger structures with structural members in vertical and horizontal directions as well as taking advantage of existing connections. A project from the Netherlands (CIP2F) following this approach, extracted 3D units from a multi-residential building, displayed in Figure 25.

Figure 25. Extracted 3D units from the Super Circular Estate project in the Netherlands (Elma Durmisevic, 2019).

Before cutting the floor slabs and walls, the units and the apartments nearby needed to be reinforced to ensure structural integrity. The units were then lifted out by a crane and reused as structural frames for single-family houses, as shown in Figure 26. While this approach enables modular planning with reused elements, it restricts flexibility in future use and layout design. While the final project report states that energy intensity and associated costs make this method not feasible, it shows on the other hand the technical viability of 3D units.

Figure 26. Lifting out and reinstallation of the 3D units (Elma Durmisevic, 2019).

A new design approach focused on the re-utilization of floor slabs, uses long flat pieces of CIP to achieve low-carbon designs (Küpfer et al., 2024). The new design method aims to use the tensile and compression strength of the reinforced concrete, rather than limited to compression as in case study CIP3F. For this design approach, a web tool (https://flore.epfl.ch/) was developed, considering various design parameters, allowing a comparison of three different scenarios, and estimating upfront greenhouse gas emissions.

As mentioned in Chapter 4, element reuse is preferred to repurposing and remanufacturing. However, for various reasons, this can be not achievable, especially for CIP as elaborated within this chapter. Furthermore, the other strategies should not be seen as invalid options as they still improve the circularity of building elements. In a pilot project (CIP4F) parts of CIP floor slabs have been cut out to be remanufactured as point foundations for timber columns. The slice plane was covered with mortar to protect the exposed reinforcement, for corrosion protection. In Figure 27 the placement and reassembly of the parts can be seen. The two concrete blocks were connected with rebar installed in predrilled holes and fixed with mortar. The voids around the blocks then have been filled with concrete. As stated in the project report, the cut-out pieces were part of a partly demolition process and would have been landfilled otherwise (Flückiger + Bosshard AG, 2022).

(©Martin Zeller) (©Flückiger Bosshard)

Figure 27. Cut-outs from floor slabs were reused as foundations. (Flückiger + Bosshard AG, 2022)

The project Lumi in Uppsala from Vasakronan (CIP1F) reuses 80% of the existing in-situ concrete frame from an old office building from the 1970s. The elements have not been removed but the structure was reused in entirety. Non-destructive testing of the 50-year-old concrete verified a remaining service life of 52 years, despite carbonation depth exceeding the waterproofing layer.

Research outcomes

CIP floor slabs present a common construction type in multi-residential buildings. Therefore, expectingly an increasing number of buildings with CIP floor slabs will reach their EOL shortly. The recovery of CIP slabs poses challenges due to undefined connection areas and greatly customized reinforcement layouts. Extracting individual elements from a monolithic slab becomes more difficult with this approach. However, a possible sawing pattern and details to consider within have been stated. Furthermore, methods like 3D units and piecewise reuse of concrete are valid alternatives to increase the circularity of CIP floor slabs. However, the practical implementation of reused, remanufactured, or repurposed in-situ concrete slabs is still limited. Further pilot projects can improve the confidence of stakeholders in the practice of circular economy regarding CIP floor slabs.

6.2.2 Hollow-core slab

The hotspot analysis showed that hollow-core slabs (HCS) possess an improved GWP performance and are frequently used in multi-residential buildings. Furthermore, precast elements promise a high reusability value. The prefabricated nature provides a certain degree of modularity, given that the boundaries between the individual elements remain defined after construction.

Deconstruction

Even so, the recovery of these elements must be conducted meticulously and with careful planning to guarantee the quality of the reclaimed materials. This involves pre-demolition audits to predict the material flow of the building. The case studies HCS3 and HCS4 analysed existing office buildings in Stockholm that are planned to be demolished to determine to what extent HCS elements could be reused for new constructions. The inventory assessment including non-destructive testing of the concrete, showed that respectively 8800 m^2 and 1300 m^2 are in condition to be reused. However, it is not stated explicitly if these estimations consider losses during deconstruction.

The Återhus project in Sweden developed and tested a dismantling method to increase the recovery rate of elements. The focus of the project was on prefabricated, and in-situ cast concrete elements. Figure 28 is showing the steps to ensure the recovery and reuse of concrete floor elements. It contains technical details necessary for the practical implementation of this concept for example how to install the wire braid under built-in conditions. The connections on the short side can be cut using a diamond saw, and once disconnected, the elements can be lifted out of their position using a crane or a similar lifting device. For structural and sound-proofing reasons HCS often has in-situ concrete toppings, which need to be cut first (G.J. van den Brink, 2020). Following the removal the elements have to be cleaned of leftovers of mortar and concrete topping. The examination and classification of the elements are described in chapter 6.1.1, given that this is universal for all concrete elements.

1. Demolition to bare structure system.
2. Installation of temporary support structure.
3. Drilling holes in casted joints between the slabs (Diameter 50 mm).
4. Saw cutting of element short sides.
5. Wire braid is installed around the element with an angled pulling position.
6. The crane pulls on each braid, resulting in a cracking of the long side connections.
7. The element is lowered back onto the support again.
8. Repositioning of the element so that it lies straight.
9. Lifting of the element.
10. Removal of grout and topping when the element is on the ground.
11. On-site handling with wheel loader (Fork attachment).
12. Conventional assembly on new supports.

Figure 28. Dismantling method by Återhus (Translated from (Malaga et al., 2023a)).

CE strategies

After deconstruction and assessment, the elements need to be prepared and modified for their future application. HCS does not only have a function in the structural system but also as a partition between spaces thereby ensuring functions of privacy like noise-proofing. In a re-design case, G.J. van den Brink (2020) notices that HCS taken out from office buildings are difficult to reuse in residential buildings because of sound and fire safety reasons since in commercial buildings the requirements are often lower than for dwellings. The sound issues could mostly be solved by applying a floating floor while achieving the required fire class by applying glass wool plates to the bottom of the slab element. Of course, installing a floating floor will reduce the available free height of the room and also add weight to the slab element. This consideration is particularly important when reusing elements in renovation projects, as supporting structures such as columns for the floor slab may remain within the building and already predefine the available room height.

This was the case in the Kristian Augusts gate 13 project (HCS1), where reused HCS could only be used on three floors given that the structural capacity of the existing pillars was already reached (Entra ASA, 2021).

G.J. van den Brink (2020) states that geometrical modifications of HCS, like shortening in length, do not influence the bending moment capacity given that the reinforcement is constant within the element in the longitudinal direction. If the structural capacity is not sufficient, G.J. van den Brink (2020) proposes the idea of reinforcing the HCS element by adding new concrete on top and a reinforcement net on the bottom. Alternatively, strips of carbon fibre can be glued on the bottom of the element to increase the tensile strength. However, G.J. van den Brink (2020) refers to the findings of N.R. Naber (2012) that these techniques are too expensive and additional materials make them not sustainable enough. If this is the case another circular pathway should be chosen for this element, for example repurposing or recycling of the materials.

Connections

The reassembly of the HCS will be slightly different from new elements since one or multiple cores are filled with mortar and rebar steel from the former connection between the HCS and the supporting wall. This will limit the possibilities of connecting the slab with the wall at any location of the HCS element (Naber, 2012). Given that and considering a possible third service life, easy-to-install and demountable connections should be used. This agrees with Naber (2012), that systems that don’t require connections between the cores and other elements, like walls, are more suitable. However, a structural system with a slab between the walls, like Figure 29 a.) are only realizable for buildings up to six floors. Exceeding building heights requires improved load transfer and therefore different construction systems (Naber, 2012). The concrete cantilever bedding used in Figure 29 b.) enhances load-bearing capacity but compromises the element's future reusability. However, both connection types pose challenges in combining a reused slab element with reused walls, primarily due to the anchors required within the wall. Installing these anchors in second-hand concrete walls demands considerable effort. Therefore, it may only be valid for constructions with newly casted walls.

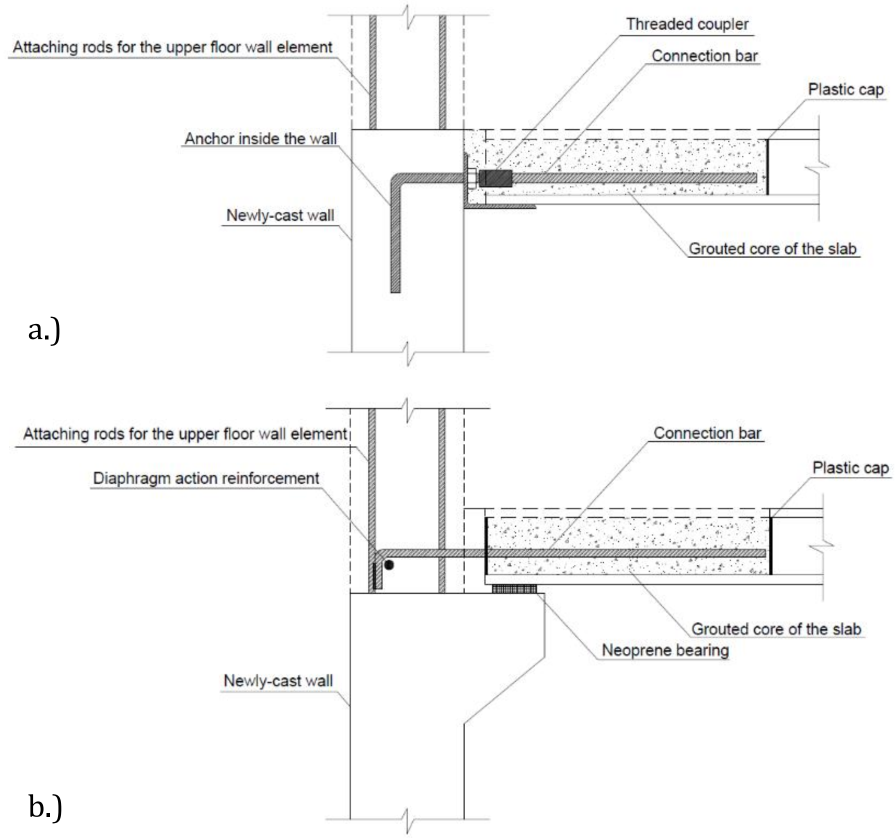


Figure 29. Exemplary connection types for easy mounting and deconstruction. For visual representation only, not in scale. (Volkov, 2019)

For connections between the slabs, low-strength mortar connections represent an acceptable trade-off between reusability and load-bearing ability (G.J. van den Brink, 2020; Noordhoek, 2022). Depending on the structural framework increased horizontal shear resistance may be needed. For this reason, the grouted connection can be reinforced by steel plates on the top and bottom of the connection, as shown in Figure 30.

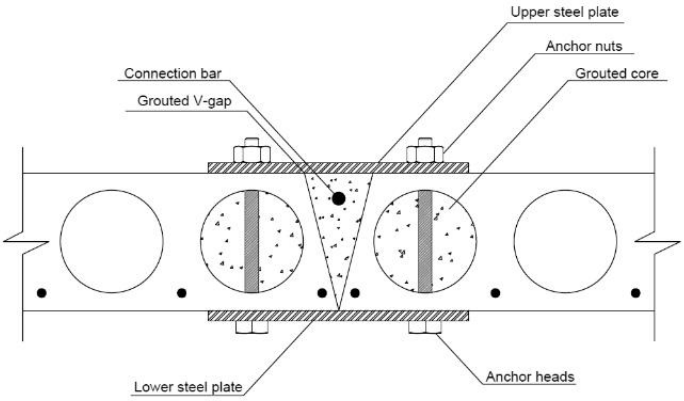


Figure 30. The longitudinal connection between slab elements with improved shear resistance. (Volkov, 2019)

Case studies

The design study done by G.J. van den Brink (2020) shows that thorough design of new buildings can significantly increase the number of reused elements. Through improvements based on observations from the first design, the reuse rate for HCS was enhanced from 74% to 100% in the second building design.

G.J. van den Brink (2020, p.144) suggests looking into the possibility of 'copying' the structure from the office building to improve the reuse rate of the new design. Noteworthy is also that for the second layout, the reused elements were extracted from two buildings while for the first case, three donor buildings have been used. This means that a more suitable selection and adjusted design have a higher success rate, rather than having a large selection. Case study HCS2, the Hållbarhetshuset located in Stockholm, is a great example of this approach. Within the project, an old garage from the 1970s was dismantled and at the same location, an office building was constructed. The project managed to cover 100% of the required floor slabs with reclaimed HCS. All elements have been reused thereby avoiding large transportation distances, long storage times, and more direct access to the elements to ensure their quality and measurements.

A noteworthy case study is the Kristian Augusts gate 13 project (HCS1) from Norway. An existing office building was redeveloped and extended. For this process materials from 25 different donor buildings have been used, including 160m^2 of reclaimed HCS elements. It is not stated what percentage of new HCS elements replaced the reused elements in the building, despite an overall reuse share of 80% being achieved. As a result of work conducted at HCS1, Norway introduced a standard in 2022 that outlines guidelines for the reuse of hollow-core slabs (Standard Norge, 2022). The standard considers planning, logistics, quality, and documentation of reused elements (Steinar Valbø, 2023).

Two more recent projects show the increasing popularity of the use of circular building elements. Case study HCS5 showcases again the possible recovery yield of HCS elements salvaged from buildings not designed for reuse. An amount of 3000m^2 HCS was recovered from an old IKEA building built in 1972 in Gothenburg. The analysis of the HCS elements determined them suitable for reuse and an estimated residual lifetime of around 100 years (Framtiden Byggutveckling AB, 2024). The elements are planned to be reused in a residential building in Gothenburg.

The other project HCS6, 300m^2 of HCS was reused from a demolished residential building in an office building. Therefore, the elements were transported 250 kilometres, which required a large logistic effort. According to the implementing construction company, 30 tons of carbon dioxide have been saved by reusing the floor elements.

Research outcomes

The large amount of case studies, when compared to the other elements, enable an impactful insight into the reuse of HCS. The fact that an increasing number of projects already reuse HCS elements not only displays the technical feasibility but also the growing interest and confidence in circular building elements. The publication of the Norwegian standard enables a unified process for deconstruction, testing, and CE certification, which is of immense importance for CE trustworthiness. Furthermore, the current findings related to mechanical properties and durability seem to be promising. However, multiple case studies have shown that HCSs are prone to fail requirements for fire safety and soundproofing.

Additional design effort and material are necessary for the re-application of new constructions. One major downside discovered during the literature review is the lack of alternative circular strategies. Due to their lightweight optimized form and minimal reinforcement, repurposing or remanufacturing HCS elements can be challenging. Consequently, HCS elements classified as non-reusable will be recycled, which is still a valid circular strategy. However, this limitation does affect the circularity potential of HCS.

6.2.3 Cross-laminated timber

In recent years cross-laminated timber (CLT) has become a popular timber element. Partly because of its mechanical properties but also as an environmentally friendly replacement for concrete and steel elements. Cross-laminated consists of separate timber boards glued together, each layer perpendicular to the previous. CLT is installed as individual elements therefore decreasing the difficulty of deconstruction, given that the connections are clearly defined. General challenges and limitations concerning wooden elements are discussed in Chapter 6.1.2. On a commercial scale, CLT began to be used in Europe around the year 2000, which means the oldest CLT elements have been in use for approximately 25 years. Consequently, there have been relatively few demolition projects involving large amounts of CLT conducted thus far, necessitating a higher level of assumptions for EOSL scenarios.

Deconstruction and recovery rate

The Professional Committee for the Development of the French Furniture and Wood Industries (CODIFAB) created reference reuse scenarios for CLT wall panels, floor panels, and glulam beams based on data from the French timber industry (CLT1, G1). Furthermore, the respective study conducted a questionnaire survey filled out by manufacturers and performed data collection from 11 different new construction sites where CLT elements were reused. Based on the gained data an environmental analysis in the form of an LCA was done to assess the ecological impact of reusing timber elements.

In case study CLT1 it was assumed that the reused panel would replace a new panel with an equivalent thickness of 80% of the reused panel to account for lower material quality for the reclaimed timber. Applying a value correction factor after EN15804 A2 Annex D. The reference reuse scenario includes values for recovery yield, technical equipment, transportation distances, and reconditioning measurements (Vial & Mandrara, 2022, p. 16). The project committee initially emphasized that the length of elements, rather than their thickness, serves as a criterion for assessing reuse potential. Considering the observed minimum floor span of three meters in French construction practices, the analysed CLT floor panels must also be at least three metres in length to be considered suitable for reuse (Vial & Mandrara, 2022, Chapter 5.1.4).

According to CODIFAB the most common connections for CLT elements are displayed in Figure 31 and the disassembly involves the following dimension losses for each panel,

- In length: 200 mm, on each side 100 mm to disassemble the wall floor connection,
- In width: 160 mm, on each side 80 mm to disassemble the panel-to-panel connection.

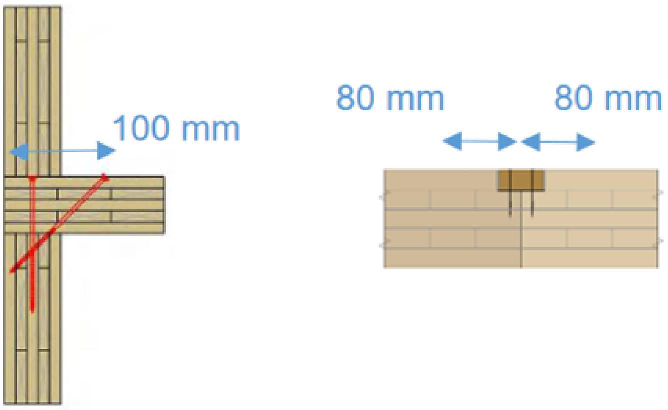


Figure 31. Visualization of assembly cut-outs for CLT floor panels (Vial & Mandrara, 2022).

The findings from 11 site analyses, containing over 3415 CLT elements, are detailed in Table 7. On average, 76% of CLT panels were retrievable from these structures, although with considerable variation between the minimum and maximum values. The highest decrease in recovery rate could be observed for lengthwise selection and the majority of the cases only showed a small difference (≤ 1%) between removal of recesses and assembly cut-outs.

Table 7. Overview of analysis of CLT flooring projects (Vial & Mandrara, 2022, p. 24).
(Rounded to one decimal)

	Recovery rate after removal of recesses [%]	Recovery rate after assembly cut-outs [%]	The recovery rate for length ≥ 3m [%]	Average surface area recovered per panel [m²]
Mean	93,0	89,9	76,0	9,4
Min	75,3	70,1	42,2	5,9
Max	99,0	99,5	94,0	18,2

However, not only does the recovery rate need to perform well but also the yield out of the reclaimed elements when remanufacturing. The test from Chúlain et al. (2023) achieved a rather low yield of 28% caused by cutting to length. This could be increased to around 70% when panel sizes used in buildings are similar to the dimensions required for CLT production (Chúláin et al., 2023).

Testing

Destructive laboratory testing is crucial to increase knowledge about the mechanical properties of aged and salvaged timber. However, for field operation, accurate, reliable, and practicable non-destructive testing methods have to be available.

A comparison of results for the two testing methods in a full-scale element experiment shows that the MOE of secondary timber quantified by non-destructive testing can be used to predict the bending stiffness of the CLST element (Dong et al., 2024). Linear relationship analysis furthermore showed that the predicted bending stiffness is more accurate when using the average dynamic MOE of the reused timber determined in a longitudinal direction (Dong et al., 2024). The analytical models in the Canadian CLT handbook offered a conservative method for predicting the strength and stiffness of CLST.
Further improvements were achieved by accounting for homogenization effects through a bearing model (Dong et al., 2024).

CE strategies

Element reuse of CLT floor slabs proves to be challenging, mainly due to the uncertainties of the mechanical performance and respective grading of aged timber. Another reason is as mentioned the short service life of CLT elements to this day, restricting the practical implementation for element reuse.

For this reason, hybrid alternatives were investigated, consisting of a mix of new and reclaimed timber, including low-grade timber. Concerns when using low-grade timber in load-bearing structures originate from the increased number of defects in the timber compared to structural classified wood. The analysis of residential buildings with different construction types in Finland, Ireland and Spain showed that even masonry and post-beam constructions possess useful quantities of timber. In masonry buildings in Ireland, an average of 0,031 m^3/m^2BTA of timber was found. For post-beam and CLT constructions located in Spain, this number increased to 0,085m^3/m^2BTA and 0,2-0,3m^3/m^2BTA, respectively. This only accounts for timber suitable for element or material reuse. which shows that constructions not made from massive wood still enclose significant wood quantities suitable for material reuse within CLT elements.

Several experiments and case studies have been conducted for using reclaimed timber in the production of CLT, sometimes named cross-laminated secondary timber (CLST) due to the use of secondary timber within the element. Different setups were used where the CLT elements consisted either purely of salvaged wood or a combination of reused and new layers. A CLT completely made of virgin material usually serves as a benchmark for the mechanical properties.

At the University of Galway, softwood timber boards recovered from roof trusses of a building from the 1970s were reused in CLT elements and tested against a newly produced element. Three different cases were created, the first with reused wood only (RRR), the second with new layers on top and bottom and old wood in the core (NRN), and the third complete of new timber (NNN), with the tested CLT elements consisting of three layers in total. The conducted study found no major difference in the mechanical properties of bending strength (MOR) and modulus of elasticity (MOE) of the tested elements (Chúláin et al., 2023). The findings for MOE coincide with results from Llana et al. (2023) which found comparable elastic behaviour for CLT made from new and recovered timber. However, the maximum load for the elements RRR and NRN was significantly lower than for NNN.

Additionally, they tested a CLT element with reclaimed wood for the outer layers and new in the inner layer (RNR) which showed for both MOE and MOR similar performance as the CLT element of new timber.

Based on these results it can be concluded that for the transverse layer the material choice, new or reclaimed wood, does not affect the MOR performance of the element (Llana et al., 2022; Rose et al., 2018; Stenstad et al., 2021). Despite inferior mechanical properties, the results show that the elements consisting of recovered timber are still suitable for structural use (Llana et al., 2022). Additionally, several studies showed that due to the layering in a perpendicular direction in CLT elements, a homogenization effect occurs, which decreases the influence of the defects in the individual elements (Brandner, 2013; Concu et al., 2018; Dong et al., 2024). The manufacturer NordCabin already uses CLST as a load-bearing structure in small wooden cabins, proving that commercial use is possible (Cabin, n.d.; Yap Shi Quan, 2022). Although the dimensions and load requirements of a small cabin are hardly comparable to a multi-storey residential building, the main principle of safe load transfer and sound functioning of the element remains the same.
A general failure point of CLT elements is the bonding between the individual components. New panels must fulfil the requirements stated in EN 16351:2015 concerning delamination and shear strength. A series of tests of CLT panels with recovered wood proved that the performance of bond strength is equal to new timber panels (Uí Chúláin et al., 2021). The passing rate for CLT elements exclusively made with recovered wood was significantly higher than for new timber elements. This could be explained by the rougher surface of the old timber even after identical surface preparation (Llana et al., 2022).

Research outcomes
Recent case studies and pilot projects showcased technical possibilities to increase the circularity of CLT. For element reuse, no pilot projects with practical implementation were found. This could be attributed to the fact that buildings incorporating CLT elements have not fulfilled the designed service life (Stora Enso, 2020). Therefore, the amount of CLT elements subject to EOSL scenarios is limited. Though, an increasing number of case studies are conducted about the remanufacturing of old timber into new CLT elements. Small-scale testing in a laboratory environment implies sufficient structural performance of CLST to be used as a primary load-bearing structure.

6.2.4 Glulam

Glulam, short for glued laminated timber, is a versatile engineered wood product composed of layers of dimensioned lumber bonded together with adhesives. Glulam is referenced here, although it is not commonly used as a floor slab but rather as a primary supporting structure for floors. Typically, in the form of beams or frame portals, it is often combined with the other floor elements studied in this work. Glulam represents a high-strength structural timber element that requires significant energy input during manufacturing, which can be mitigated or minimized through circular options.

Deconstruction and recovery rate

Case study G1, more in detail described in 6.2.3, includes a comprehensive study of the reuse of timber elements. This includes a reference reuse scenario and an analysis of four construction sites to obtain data for the recovery rate of glulam elements. Contrary to CLT, connections for glulam differ strongly from manufacturer and type of use. Furthermore, glulam involves larger dimensions in length, width, and height, thus, in turn, increasing the size of the connections and possibly the necessary cut-out when disassembling. This was specified by the manufacturer for one of the sites as a deduction of 20 cm at each end of the beam and 20 cm at the middle support. For the remaining sites, the resulting losses for disassembling were defined as 15% of the span of the element. According to these conditions Table 8 displays the obtained data from the site analyses. With a mean recovery rate of 85% glulam elements show promising circular value and compared to other elements easier deconstruction.

Table 8. Recovery rates from the sites involving glulam (Vial & Mandrara, 2022). (Rounded to one decimal)

	Recovery percentage [%]
Mean	85,0
Min	99,5
Max	87,7

CE strategies

Similar to CLT, glulam elements can be increased in circularity by reusing recovered wood from demolished buildings. Comparing 5-layered glulam beams made from recovered and new timber showed no significant differences for MOE but lower bending strength for the recovered timber. Nonetheless, the obtained value (MOR = 31,87 N/mm^2) are still high enough for structural applications (Llana, González-Alegre, et al., 2023). Furthermore, in the course of the EU-project CIRCuIT, the shear strength of glulam beams remanufactured by reclaimed wood was tested and showed similar performance as new glulam (Sandberg et al., 2022). A downside of the remanufacturing process is the substantial amount of waste wood generated. Although, the glulam element was entirely made out of reclaimed timber, the resulting yield in the study of Llana, González-Alegre, et. al (2023) was only around 13%. This will require significant improvement to ensure the sustainability of this CE strategy.

Assessment and testing

The G4 project analysed an approximately 50-year-old timber frame system of an old textile factory, to determine the reuse potential of the glulam elements. In particular, the detection of mould on the top of one of the beams was of great interest due to its potential impact on the timber. For this purpose, an on-site mind map was developed to categorize the existing structure using visual observation of anomalies and defects, such as cracks, the presence of insects, and discolouration of the wood. The mind map features yes/no questions covering non-destructive and semi-destructive testing techniques. Displayed in Figure 32 is the overall structure of the mind map; each indicator contains a separate mind map, attached in Appendix B.

The outcome from the indicator mind map will classify the element into three different reuse categories: High reusability potential, reusable with conditions, and rejected. Within the testing of the elements, two main observations were made regarding the future reuse assessment of glulam. Firstly, when following the standard for new timber Young's modulus results in lower wood strength classes, compared to bending strength. Hence, it appears adequate to solely establish the modulus and designate it as a grading criterion. Secondly, the detected mould on the beam influenced the glue properties in a significant way but not the properties of the wood (Yahmi et al., 2023). This also confirmed the effectiveness of the discolouration map, classifying this section as reusable if mechanical properties are verified.

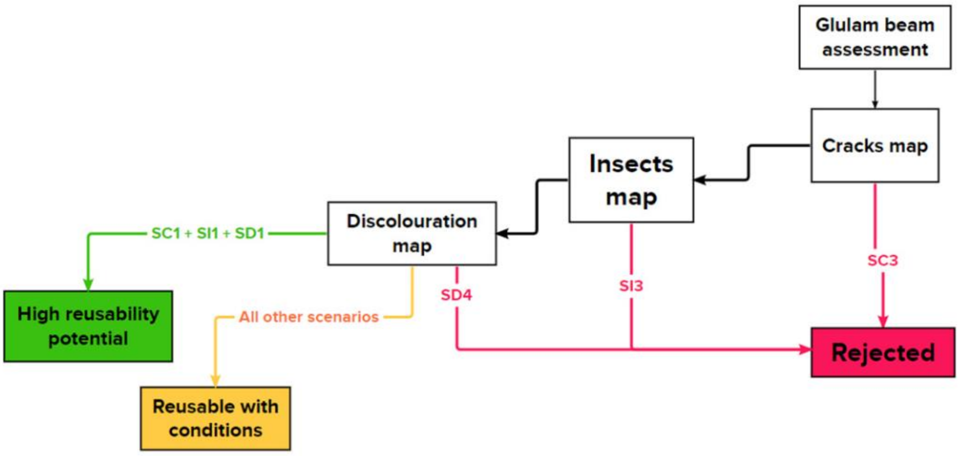


Figure 32. Assessment mind map for reuse potential of glulam (Yahmi et al., 2023). SC=Scenario crack; SI=Scenario insect; SD=Scenario Discolouration.

Case studies

A prominent pilot project for the reuse of structural elements is the C.K. Choi building at the University of British Columbia in Canada (G3). It is regarded as one of the world's first green buildings. Consisting of a timber frame structure, 90% of needed timber elements were reused glulam from a 75-year-old building, demolished adjacent to the construction site. The initial visual grading of the reclaimed structural elements led to a rejection of all elements with signs of previous usage. This could be massively increased using a more detailed evaluation with a tight collaboration among the structural engineer and the timber grader, showcasing the high uncertainty of visual grading of recovered wood and the need for a new grading system.

With missing standards and uncertainty in the mechanical properties of aged wood, conservative dimensioning could be an opportunity, as showcased in G2. A timber frame from an ice rink built in 1970 was reused in agricultural structures in the year 2019. The elements are used in their original intent but with lower demand as a load-bearing structure. Unfortunately, there are no details on the recovery and reinstallation process.

Case study G5 shows that circularity can also be applied during the use phase of the building during renovations for instance. In this project, a 24-year-old temporary building was investigated through an early material audit which allowed the majority of the glulam elements either to be extended in their service life and kept in their original use or to be reused in a different use as primary and secondary frameworks. Presumably without the pre-demolition audit, the majority of the glulam elements would have been discarded.

Research outcomes

Inventory analyses of glulam buildings have revealed promisingly high recovery rates, indicating significant potential for the reuse of glulam elements. Limited tests on remanufactured glulam have demonstrated structural quality, enabling the integration of secondary timber components. In a case study (referred to as G4), a mind map approach was developed for rapid assessment and classification, followed by the necessary tests required for verification. This assessment guide could prove invaluable for contractors contemplating the reuse of glulam elements, providing a structured framework for decision-making and ensuring the structural integrity and safety of repurposed materials.

6.3 Load-bearing walls

Load-bearing walls are one of the crucial building elements for transferring loads in the structural system to ensure the structural integrity of buildings. Through hotspot analysis, one of the major data points indicated that walls were the highest contributors towards CO_2 emissions. The circular strategies being studied for wall reuse stood out at the top hierarchy of all. The wall types and materials are discussed below in this chapter.

Reusing concrete has been seen as one of the most challenging strategies to follow when talking about making concrete circular, even though, there have been many studies showcasing the significant environmental impact. In the current context, most of the load-bearing components get discarded even though they are still in good condition and have full capability for serving similar load-bearing purposes.

Table 9. Overview of case studies and pilot projects involving load-bearing walls.

Code	Details to elements*	Type of study	Building type	Date
CIP1W	Cast-in-place walls	Offsite reuse	Multi-residential building	1997
CIP2W	Cast-in-place	Onsite reuse	Residential building	2019
CIP3W	Cast-in-place	Repurposing	Basement walls to footbridge prototype	2021
CIP4W	Cast-in-place walls	Inventory analysis	Multi-residential building	2023

Code	Details to elements*	Type of study	Building type	Date
			Storage building	
CIP5W	Cast-in-place walls	Theoretical onsite reuse	Multi-residential building	2024
CIP6W	Cast-in-place walls	Repurposing	Parking pavement	2021
PC1W	Precast system wall panels	Onsite reuse	Multi-residential building	2005
PC2W	Precast system wall panels	Offsite reuse	Multi-residential building	1986
PC3W	Precast walls, inner + outer	Offsite reuse	Residential building	2001
PC4W	Precast walls	Theoretical offsite reuse	Multi-residential building	2020
PC5W	Precast walls, slabs, beams	Connection design for reused elements	-	2019
PC6W	Precast walls, slabs, beams, columns	Theoretical offsite reuse	Multi-residential building	2013
PC7W	Precast wall panels, inner + outer	Offsite reuse	Prototype	2010
PC8W	Precast structural frame	Offsite reuse	Multi-residential building	2008
PC9W	Precast system wall panels	Offsite reuse	Prototype	2004
PC10W	Precast walls, inner + outer	Planned offsite reuse	Community centre	Planned for 2024/2025
CLT1W	CLT Wall panels (3x6m)	Offsite reuse	Prototype	2016
CLT2W	CLT wall panels	Data collection, LCA study	-	2022

CIP = Cast-in-place
PC = Precast
CLT = Cross-laminated timber

W = Wall (addition to distinguish between floor and wall elements made from the same material)
*Only structural elements are mentioned.

6.3.1 Cast-in-place concrete walls

Based on the results of the hotspot analysis, it was found that cast-in-place concrete walls are not commonly used in multi-residential buildings. However, it should be noted that the study analysed a small volume of recent projects, and hence, the findings may not apply to older projects or buildings that are approaching their EOSL. The current EOSL practice for concrete parts is crushing and recycling into aggregates for new concrete, which reduces the need for virgin aggregate materials but often requires more cement due to the coarser RA.

Deconstruction

The deconstruction methods for CIP slabs and walls are almost identical for both elements. Therefore, most of the methods used for CIP floor slabs in the chapter 6.2 can also be adapted for CIP concrete walls.

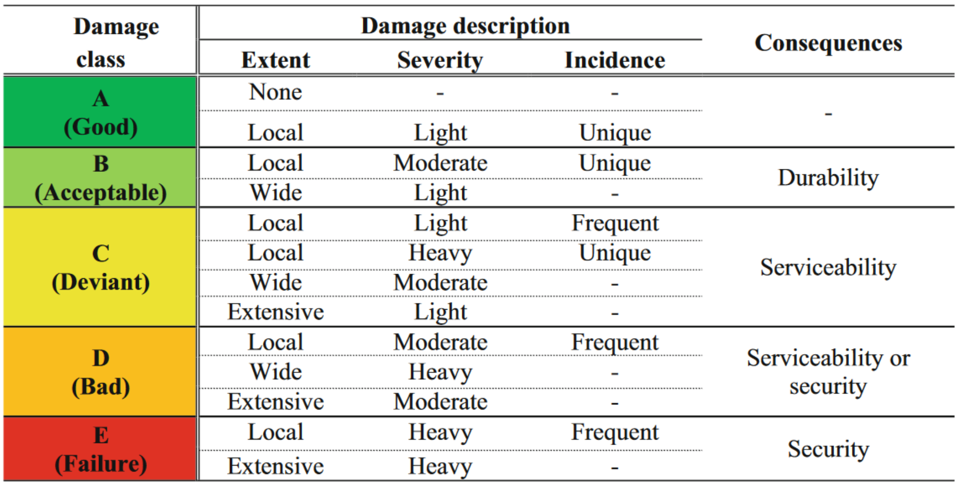
Assessment

The reusability assessment Table 10 was used for three case studies involving load-bearing structures made of CIP. However, the method can be used for all CIP structural elements when considering reuse. The first step is the inventory and evaluation of the targeted elements within the obsolete structure. In this step, amongst other things, dimensions, volumes, material properties, location of the elements as well as their exposition class are determined.

Table 10. Two-step reusability assessment. (Devènes, Bastien-Masse, Küpfer, et al., 2023)

	Step 1 Obsolete structure audit	Step 2 Reusability grading
Donor structure	Inventory and evaluation	Damage assessment
Receiving structure	-	Definition of the use and intervention classes

Step two is the reusability grading which is done for the donor and the receiving structure. The damage assessment includes visual inspection and possibly in-situ assessment of the elements. Detected damages are categorized into four classes (Figure 33), "based on the extent (local, wide or extensive), the severity (light, moderate or heavy), and the incidence (unique or frequent) of the damage" (Devènes, Bastien-Masse, Küpfer, et al., 2023, p. 445). The classes can be adjusted if additional tests after deconstruction are conducted.



Damage class	Damage description			Consequences
	Extent	Severity	Incidence	
A (Good)	None	-	-	-
	Local	Light	Unique	
B (Acceptable)	Local	Moderate	Unique	Durability
	Wide	Light	-	
C (Deviant)	Local	Light	Frequent	Serviceability
	Local	Heavy	Unique	
	Wide	Moderate	-	
	Extensive	Light	-	
D (Bad)	Local	Moderate	Frequent	Serviceability or security
	Wide	Heavy	-	
	Extensive	Moderate	-	
E (Failure)	Local	Heavy	Frequent	Security
	Extensive	Heavy	-	

Figure 33. Damage classification for reinforced concrete elements. (Devènes, Bastien-Masse, Küpfer, et al., 2023)

The visual inspection of the donor structure should provide information about the condition of the elements and mandate further testing if needed. Figure 34 shows possible damage of concrete elements, registered during the visual inspection.

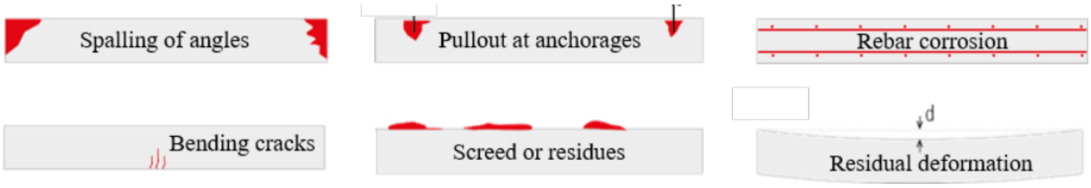


Figure 34. Common types of damage to concrete elements. (Devènes, Bastien-Masse, Widmer, et al., 2023)

The use classes displayed in Table 11, defines the point of use of the element in the receiving building. The classification is done by two parameters, stability (consequence of failure in receiving structure) and exposition to water.

Table 11. Assignment of use classes. (Devènes, Bastien-Masse, Küpfer, et al., 2023)

Use class	Lightly exposed	Moderately exposed	Highly exposed
No stability criteria	I	II	III
Self-stable	II	III	IV
Stable under external loads	III	IV	V

The intervention class describes the actions necessary to make the component suitable for reuse. Actions include modifying, restoring, and strengthening to improve the functionality of the reclaimed elements.

Table 12. Intervention class definition. (Devènes, Bastien-Masse, Küpfer, et al., 2023)

Intervention class	Maintenance measures	Geometry modifications
a	No action	No further cutting after extraction
b	Preventive maintenance, light strengthening	Simple cutting

c	Curative maintenance, rehabilitation, medium to important strengthening	Complex cutting or modification

The reusability class is determined by the combination of the damage class, the use class, and the intervention class as presented in Figure 35. The definition of the reusability class enables the determination of the optimal reuse solution for a reclaimed component. Elements graded with questionable reuse could then be considered for repurposing or remanufacturing. The method then gives an applicable tool for parties involved in projects emphasising circularity.

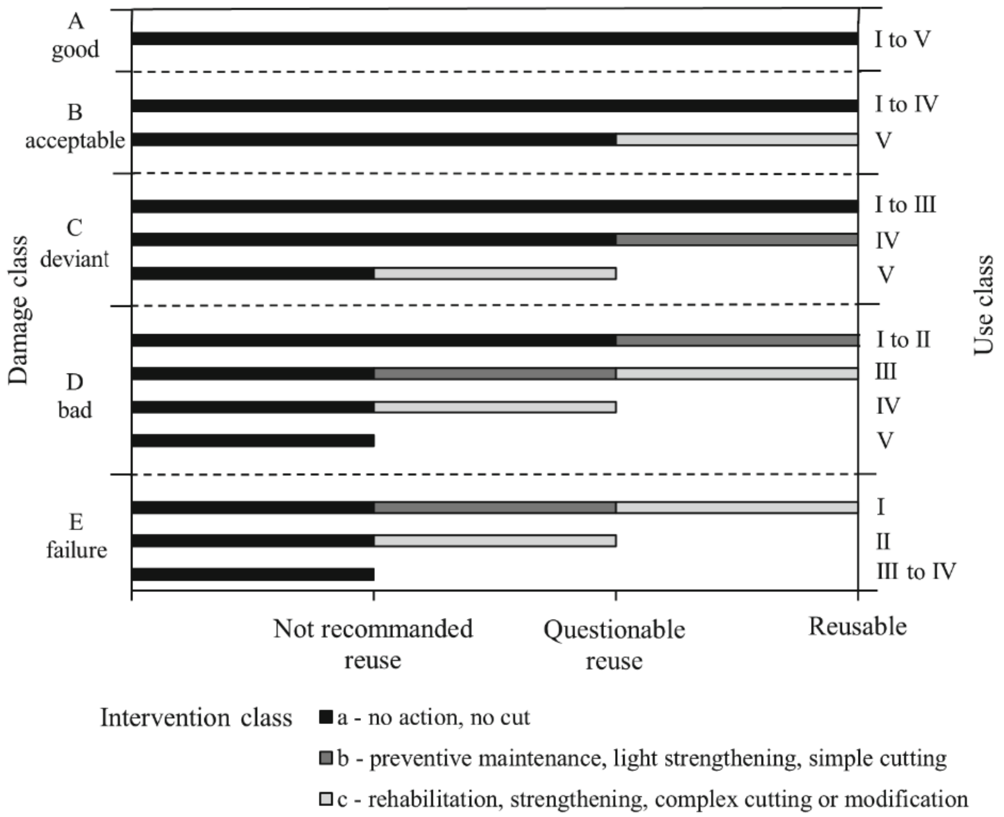


Figure 35. Reusability grading by the three classes. (Devènes, Bastien-Masse, Küpfer, et al., 2023)

Testing

The main testing method and the following classification of elements are elaborated in 6.1.1. However, essential for the performance of load-bearing CIP walls is the reinforcement. Special attention therefore needs to be paid during sawing to not damage crucial parts in the reinforcement layout. If drawings are unavailable, estimating the layout requires a combination of analytical methods, involving destructive openings in the concrete cover, and non-destructive scans with GPR. Combined with the presented reusability assessment, these testing methods are especially important for the inventory and evaluation of the donor structure, given that the elements are in a built-in state.

CE strategies

In the project Re:crete (CIP3W), concrete blocks from a CIP building were repurposed into a 10-metre spanning arch footbridge, to demonstrate the feasibility of reclaimed CIP elements to create new load-bearing structures. The elements were sourced from the basement walls and the mat foundation of a close-by transformation project. Agreeing with the hotspot analysis, in which the majority of CIP walls are located in the basement. After cutting out the pieces, post-tension steel cables were installed to increase the tensile strength of the elements. This approach was taken due to the unknown reliability of the existing reinforcement. To achieve this, holes were drilled into the sides of the concrete blocks, and cables were inserted. Prestressing ducts were then injected with mortar to prevent the cables from coming into contact with air and water. A downside of this last measure is that it makes the deconstruction of the arch for future reuse difficult. The remaining gaps between the blocks after assembly were closed by mortar connections. Although only done for a single project, this may open up possibilities for the repurposing of reclaimed concrete, given that the structural performance can be increased in the process.

Redesign and connections

According to Widmer et al. (2023) the design methodology for walls and columns to be built from reclaimed components, a similar approach as slab parts can be followed as shown in Figure 36.

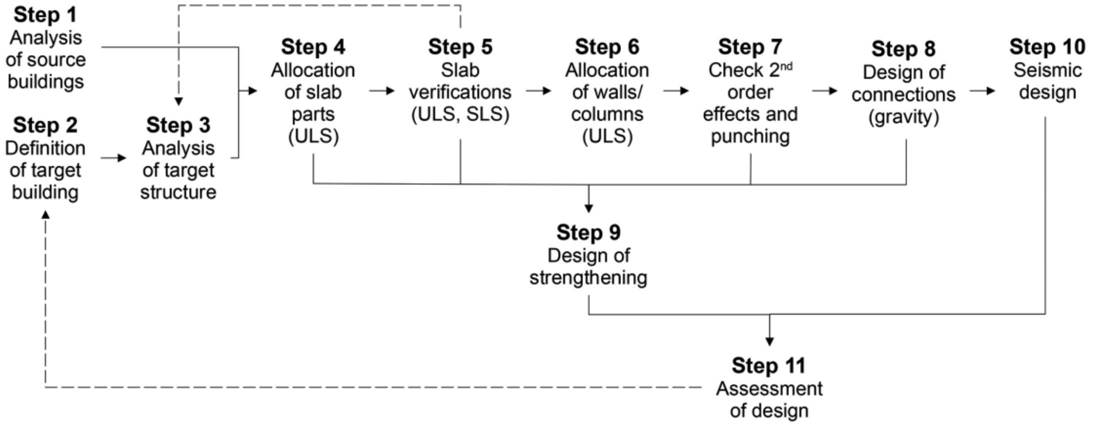
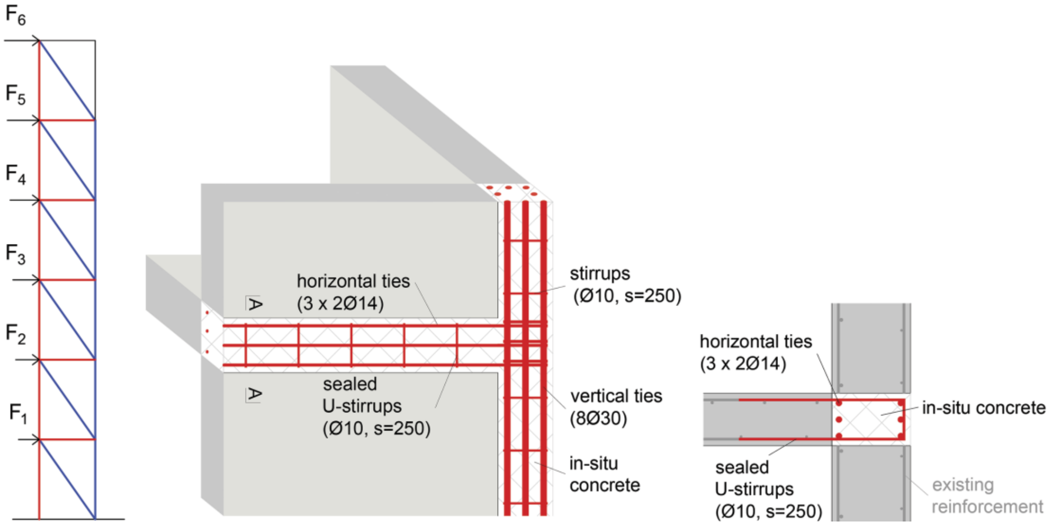


Figure 36. Process for designing a load-bearing system from reclaimed cast-in-place RC components. (Widmer et al., 2023)

The case study CIP5W is the design of a planned multi-residential building, consisting of CIP wall elements to work as a structural system. CIP5W analysed two existing office buildings, at the site of the planned building. The analysis revealed that the reclaimed components lack adequate cross-sectional resistance to withstand lateral forces. As a result, an alternative bearing system is proposed, involving the construction of each bracing wall as a truss system spanning the entire height of the building, as shown in Figure 37 a).

Figure 37 b) + c) pictures the connections between the walls, introducing new reinforcement bars embedded within cast-in-place concrete between the reclaimed wall components, serving as vertical and horizontal ties. The case study is located in Basel, Switzerland which has a relatively high seismic risk within the country. The design is done accordingly and showcases the technical feasibility of reclaimed CIP wall elements in high-demanding structural applications.



a) Truss system (red=tension, blue=compression

b) Elevation of the core walls

c) Section A-A

Figure 37. Bracing system for reclaimed concrete elements. (Widmer et al., 2023)

Case studies

The case study CIP4W contains three different buildings, two multi-residential buildings and a storage building, built between 1964 and 1975. Since all three have been analysed using the presented reusability assessment, the results are summarised in on case study in this work. The inventory analysis of the buildings for structural elements revealed that over 80% of CIP elements are in good condition, classified as damage class A (Figure 33). Considering changes for stability criteria, exposure class and intervention, 92 to 99% of the CIP elements are reusable in the identical or similar function as initially. This number will decrease after deconstruction, nonetheless, the large potential is promising.

Already presented in 6.2.1 (CIP2F), the same project is taken up shortly here again as case study CIP2W. The project involved the extraction of 3D units, including two floor and two wall elements, see Figure 25. This method avoids to a certain extent the issue of reconnecting elements, especially when both elements are reclaimed. In this case, there is less flexibility in adjusting the connections by combining reclaimed and new elements.

A case study (CIP1W) from Sweden, called the Udden project dates back to 1997 and is seen as a pilot project in Sweden for the use of reclaimed materials. Within the project, 50 larger apartments from two multi-residential buildings were deconstructed and from the reclaimed material, 22 smaller apartments (in total 1070m^2) have been built.
For the new construction, 72 CIP wall elements were reused, however, without giving specific numbers for the dimensions or surface area of these elements. A diamond saw was used for cutting the elements into operable sizes, but no details were given about the reinstallation.

Research outcomes
In a nutshell, it can be said that the two-step reusability assessment can serve as an effective tool for projects considering reuse. The split-up in donor and receiving buildings also allows the method to be used when contractors are only involved in the process of one of these structures. The significant potential for reuse of components identified in the three assessed case studies in CIP4W is an encouraging finding. The challenge is to integrate the assessment method into current practices for buildings that will soon be dismantled. Furthermore, within the chapter, a possible redesign and connection type was elaborated. The analysis of the case studies showed that, although the element reuse of CIP wall elements comes with several challenges, it has proven to be technically possible and related to Figure 35, remanufacturing and repurposing are valid circular options to prioritize over recycling.

6.3.2 Prefabricated concrete

In the hotspot analysis, precast load-bearing walls, including sandwich and half-sandwich panels, have the highest occurrence and the largest environmental impact. For this reason, emphasis should be on the circular options of prefabricated elements. As they are designed with consideration for lifting, transportation and installation after production, the initial assessment looked promising.

Deconstruction
Depending on whether the walls fulfil only a loadbearing function or also a shear wall function, they can be connected horizontally in several ways. One way is to leave a gap between the elements and fill it with mortar, without using reinforcement. The most common method of coupling shear wall elements is by incorporating protruding bent reinforcement bars on the sides of the wall. These bars overlap with the bars of the adjacent element and create space for inserting a vertical reinforcement bar. Unreinforced horizontal joints can be broken by prying and lifting. However, if there are dowels or reinforcement bars in the horizontal joint, these need to be cut with a diamond saw. For lifting, the old anchors from installation can be used, if possible. Otherwise, new anchors have to be installed by drilling holes in the top of the element. In certain cases, wall elements can be lifted by inserting lifting strops through door openings.

According to the ReCreate project, the recovery and reuse process should follow the following steps (adapted from (Stenberg et al., 2022):

1. Inventory and suitability tests
2. Deconstruction and demolition methods
3. Main inspections
4. Transportation
5. Temporary storage
6. Additional Inspection
7. Transportation
8. Reconditioning
9. Use of CE strategy: Reuse / Repurpose / Remanufacturing

Assessment

The general evaluation of the concrete elements is described in detail in 6.1.1.

CE strategies

Several case studies for the element reuse of precast wall elements could be found, which are presented in more detail later. However, four main issues were found in these studies. Firstly, most recent studies are theoretical designs of multi-residential buildings with reclaimed materials (PC4W, PC5W, PC6W). While actual buildings have been analysed for the deconstruction inventory, there was no practical reuse but optimised designing with these elements. The design approach for reclaimed materials is of great importance, however practical implementations increase the insights and common problems when reusing precast wall elements. Secondly, many of the remaining projects are small-scale prototypes without actual or only a temporary function (PC7W, PC8W, PC9W). Therefore, having limited informative value for the commercial reuse of structural prefabricated wall elements. Thirdly, the majority of the case studies involving practical implementation have been conducted before 2010 and earlier (PC1W, PC2W, PC3W). Since then, technologies for deconstruction and connections have been steadily improved, changing procedures and methods used in the reuse of precast elements. Lastly, the case studies, applied or theoretical, focus on the reuse of precast elements, which seems reasonable given that it should be preferred over the other CE strategies. However, no other CE strategy is considered or explored.

Connections

For reinstalling, the reclaimed wall elements need to be connected to slabs and adjacent walls. It therefore requires two different connection details. For a wall-to-slab connection the design in Figure 38 with the respective description below can be applied.

1. Drilling of coupling holes on the bottom of the element. Additionally, two small holes perpendicular to one large one, for the grouting process.
2. Roughening of the surface inside the holes to guarantee sufficient bond for the later injected concrete.
3. Ensure a gap between the wall element and the slab for later grouting, by a thin plate for instance.
4. Putting the wall with the drilled holes over the connection anchor.

5. Grouting of the connection sleeve by injecting low-strength concrete to the lower small hole, while the displaced air can evade through the other one.

This connection is most suitable for newly casted foundation or floor slabs, given the needed installation of the connection anchor. Installing such an anchor in a reclaimed slab element bears many challenges. However, for reclaimed floor slabs, the proposed connections in chapter 6.2.2 can be used.

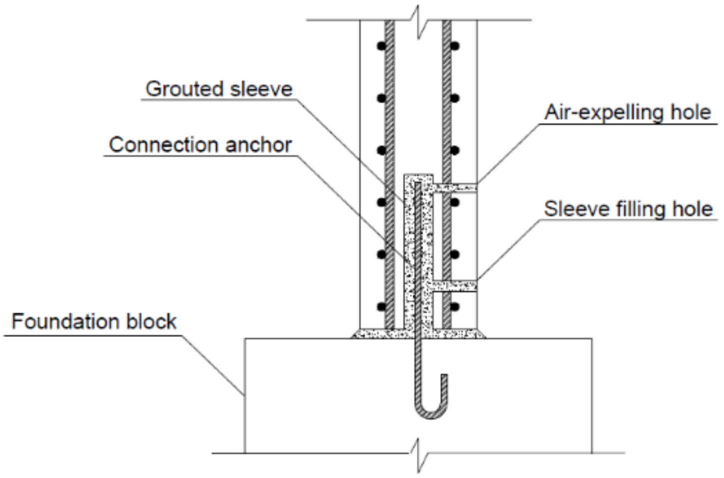


Figure 38. Wall-to-slab connection for reclaimed precast wall elements. (Volkov, 2019)

For wall-to-wall connections, the same procedure can be followed to produce a connection as shown in Figure 39. It also applies that the method is more suitable when the lower wall is newly cast for installing the anchor.

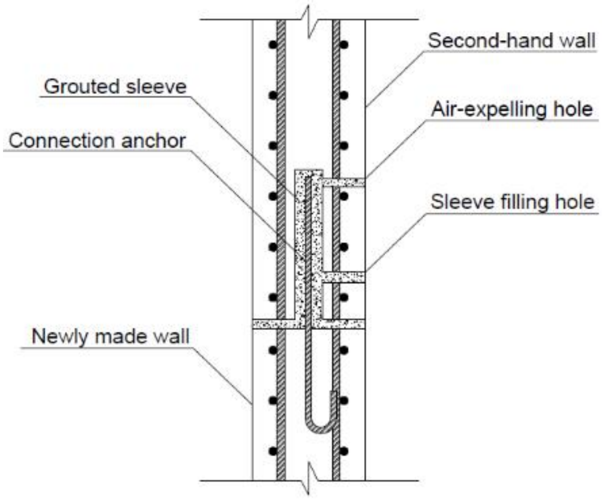


Figure 39. Wall-to-wall connection for reclaimed precast wall elements. (Volkov, 2019)

Case studies

A well-known transformation project including precast walls comes from Germany. The residential area called “Ahrsfelder Terrrassen” (PC1W) was created by transforming large multi-residential buildings into smaller ones. Thereby, the existing system wall panels have been reused, mainly due to the easy demountable connections of the panels. Additionally, with the remaining precast elements, three single-family bungalows were built.

Case study PC2W consists likewise of a transformation project. On multiple high-rise multi-residential buildings seven floors were deconstructed and the remaining building was completely renovated. Since the buildings have only been seven years old, it was decided to use the dismantled exterior wall panels to construct new houses. Approximately 900 panels have been reused in three four-storey dwellings.

For the case study PC3W, a multi-residential building in Cottbus, Germany meant for demolition was used as a donor structure for five newly built three-storey houses. Around 274 precast wall-system panels have been reused onsite in the process, avoiding transportation and the need for additional storage at another location.

The case studies PC4W, PC5W, and PC6W focus on theoretical apartment layout design (PC4W, PC6W) and the reconnection of salvaged precast elements (PC5W). PC4W and PC6W involve an inventory analysis of precast elements from an office building, along with a theoretical design exploration utilizing these elements in apartment buildings. The results of the projects showed that the structural capacity of reclaimed elements from office buildings is quite high. This is attributed to the design loads and often longer spans, compared to apartment buildings. (G.J. van den Brink, 2020). Reclaimed precast wall elements from office buildings do not meet the sound insulation requirements for apartment buildings. This is mainly due to insufficient mass, but it can be solved by adding extra layers of plaster or a decoupled facing shell. The case study also showed that the height of the elements is not a concern, as the free room height in office buildings is usually higher than in dwellings (G.J. van den Brink, 2020).
PC5W offers practical solutions for connecting reused components, as illustrated in the case study. The study includes technical details and process descriptions for creating the connections under investigation. Additionally, it outlines the advantages and disadvantages of each connection, enabling to assess their suitability for specific applications. The results from PC4W and PC6W demonstrate the potential for high reusability of office building elements in residential dwellings, particularly considering the significantly higher design loads for office buildings compared to residential ones. While theoretical, all three case studies offer valuable insights into the reuse of precast wall elements.

Small-scale studies and prototypes are essential for gaining insights and practical knowledge about the reuse of precast elements. Both case studies PC7W and PC9W were carried out as part of the "Plattenvereinigung," a German research and education project (https://www.plattenvereinigung.de/). In both projects, prototypes of pavilions constructed from reused precast elements were built to educate craftsmen in circular constructions, among other things.

In case study PC8W, three bungalows originally built for the 1972 Munich Olympic Games were carefully deconstructed and relocated for use as temporary student housing. These bungalows were exclusively constructed using precast elements, with each bungalow consisting of 13 such elements. Unfortunately, the absence of technical details or documentation for the reassembly of these elements significantly diminished the project's informative value.

The "Recreate" project, which receives funding from the EU's Horizon 2020 program, is dedicated to the development of methodologies for repurposing precast concrete elements.

For instance, there is an ongoing planning phase for a new German pilot project aimed at constructing a youth centre in the town of Hohenmölsen, with a primary objective of maximizing the integration of reused elements. According to the current design, 35 exterior walls and 25 interior walls are slated for reuse (Henschel, 2023).

Research outcomes
Several case studies have explored the reuse of precast wall elements, both on a large and small scale. Upon further examination, it is evident that there has been more extensive research on the reuse of precast concrete wall panels in Germany and the Netherlands. These case studies offer valuable insights and show significant potential for reusing precast elements. In particular, design cases have focused on optimizing apartment layouts to maximize the percentage of reclaimed elements that can be reused. For example, in the case study PC5W, detailed technical information for reconnecting the elements has been provided, allowing for more precise planning. Despite the existence of numerous case studies, the potential for remanufacturing or repurposing precast wall elements has not been thoroughly explored. Site analyses in PC4W and PC6W have shown that a significant percentage of wall elements are unsuitable for reuse and could be remanufactured or repurposed. Failing to seize this opportunity reduces the circularity of precast wall elements.

6.3.3 Cross-laminated timber

CLT walls share the same structure and composition as CLT floor slabs. Most findings from case studies apply to CLT as a composite material overall. Therefore, insights gained from case studies on CLT floor slabs, such as remanufacturing processes, are also relevant for CLT wall elements. Consequently, this chapter focuses on pilot projects specifically investigating the circularity of CLT walls.

Case studies
In a case study (CLT1W) from Japan load load-bearing CLT wall elements from a full-scale shake table test building were repurposed into a roof structure of a café, thereby serving functionally as a floor slab. Experience from CLT1W disclosed that although the design has been optimised for the dimensions of the available panels, the majority of the elements required an additional modification step before installation. Primarily caused by the former connections which limited the usable area of the elements, causing a 27% volume loss of the recovered elements. Furthermore, inadequate storage of the elements resulted in changes in dimension up to 10mm due to exposure to moisture, signifying the vulnerability of timber elements to their environment.

A theoretical case study for the reuse of CLT elements CLT2W is the same case study as F2 and is described in detail in chapter 6.2.3. The results of site analyses focused on CLT wall elements conducted in CLT2W, are presented in Table 13. An average recovery rate of 65,4 % could be achieved with a broad range of 30% between different sites. The difference between the removal of recesses and assembly cut-outs is minimal, but the recovery rate declines notably when sorting based on height criterion.

This criterion is defined according to the standard room height in France. Reflecting on the impact of height criteria on the recovery rate underscores the significance of design decisions, such as room/wall height, on the reuse potential of building elements. In terms of the average surface, a 200% difference can be observed between the minimum and maximum values. However, the majority of the recovered panels have an average surface area similar to the overall mean value. Compared to CLT floor slabs, the final average recovery rate within the analysis of CODIFAB is around 10% lower for walls. Noticeable is the significantly reduced maximum recovery rate for CLT wall elements.

It is possible that the limited range of room and wall heights could be the reason for this. When examining the figures from the site analysis, it was found that many of the sites studied had walls with an element height of less than 2 meters. These walls were likely used as small elements above doors or below windows. However, since these elements are also necessary in new constructions, limiting the analysis only to larger elements might be too restrictive.

The losses for assembly cut-outs accounted for by CODIFAB are as follows:

- In height: 400 mm,
- In width: 160 mm, on each side 80 mm to disassemble the panel-to-panel connection.

The minimum panel height was defined according to the standard building height of 2,5 m.

Table 13. Overview of analysis of CLT wall projects (Vial & Mandrara, 2022, p. 26).

	Recovery rate after removal of recesses [%]	Recovery rate after assembly cut-outs [%]	Recovery rate for height ≥ 2,5m [%]	Average surface area recovered per panel [m^2]
Mean	91,3	90,4	65,4	5,7
Min	83,4	83,1	48,5	3,1
Max	99,9	99,0	79,9	7,6

Research outcomes

The structural and functional identicality of CLT walls and floor slabs makes them predestined for repurposing. Wall elements could be used as floor slabs and vice versa. Yet, case studies regarding element reuse and repurposing are rare, but can presumably be attributed to the “young” age of CLT wall elements. The recovery rate for wall elements is lower compared to CLT floors however, this might be ascribed to the sorting criteria, especially element height.

6.4 Foundation

Foundations are the substructure part of the building. Foundations can be categorized mainly into two types i) Shallow foundations and ii) Deep foundations. Shallow foundations are mostly used in buildings or infrastructure that require lower loads whereas deep foundation is used when the load needs to be transferred to a deeper load-bearing stratum.

The hot spot analysis carried out in Chapter 3 indicated that even though the volume for the foundation element is low compared to other elements, the GWP contributions still indicated a significant contribution. The foundation is one of the elements where the usage of concrete is unavoidable. For instance, different material alternatives such as concrete, steel and timber are available for piles themselves. However, for the foundation plate of the building, concrete seems to be the most reliable and unescapable material. This in turn adds to the challenges and problems that persist in incorporating the construction of a foundation in the circular loop for now. Several factors account for influencing the environmental impact of the foundation such as the building load that determines the type and dimension of the foundation along with the selection of building materials used for the foundation (Pujadas-Gispert et al., 2018). The GHG distributions for most of the foundations come from materials rather than equipment and materials regardless of the foundation type (Pujadas-Gispert et al., 2018).

Although the concept of reuse of foundations can be dated back to the 1600s during the great fire in the UK, where new buildings were only allowed to be raised if they were built on old foundations. In most of the building construction, a major part of the structure contributing to GWP is from foundation (Butcher et al., 2006). Developers, builders, and building insurers perceive the foundation as the most difficult structural element to be considered in terms of reuse and circularity due to uncertainties related to the reliability of assessing the condition and capacity of existing foundations (Addis, 2006). However, there have been a few pilot projects on the rise to overcome those barriers and challenges. In the past decade, new technologies and techniques have been developed, which show reliable results in promoting the reuse of the foundations or adapting to build using recycled content. The relative environmental impact for the amount of embodied foundation in terms of materials used, during installation and operation reuse of existing foundations in new buildings showed precedence over using foundations with recycled materials installing new foundations, and removing existing foundations with new foundation (Addis, 2006).

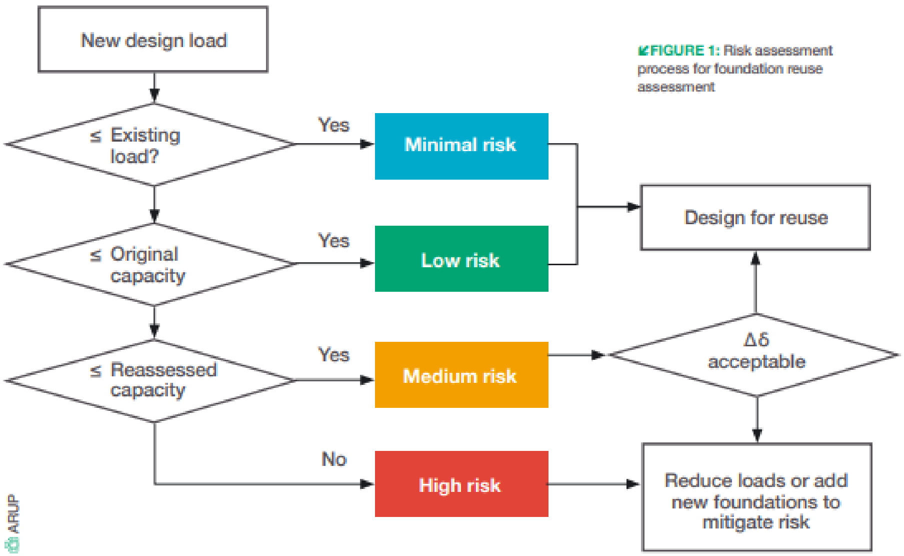


Figure 40. Risk Assessment for reuse of foundation. (Tayler, 2020)

A framework adaptation must be carried out to properly validate the feasibility of reusing the old foundation for a new structure including assessment techniques for existing foundations discussed for reuse of foundations in-situ and ex-situ (Tayler, 2020). Instead of going the usual approach of decarbonization method business as usual), the reuse of the existing foundations should be considered. Before, consideration of foundation reuse, a proper risk assessment needs to be followed to characterize the reuse potential of the foundations. In Figure 8, the foundation assessment process is elaborated in a flowchart for deciding the reuse potential of the foundation since the success of foundation reuse depends on the relation between the existing configuration and the future needs of the building.
Even among the main structural elements, foundation reuse possesses to be one of the main contributors to reducing GHG emissions. In 2023 the first annual conference regarding foundation reuse was held in Amsterdam, issues such as decarbonization of the foundation industry, addressing the technical challenges with reuse, and researching viable solutions towards sustainability of foundations were discussed. With the increasing number of buildings, the number of old piles increases below the ground level, and it will continuously increase especially in urban centres of cities. Most of the projects that show significant reductions in their GHG emissions involve case studies that have a more circular approach to building foundations.

Table 14. Overview of case studies and pilot projects involving foundations.

Code	Details to elements*	Type of study	Building type	Date
PL1PC	Pile foundation Precast concrete piles	Onsite reuse	Chemical plant	2023
PL2CIP	Cast-in-place piles	Onsite reuse	Mix-used commercial building	2022
PL3ST	Pile foundation (steel)	Onsite reuse	Bridge	2023
PL4T	Timber piles	Onsite reuse	Industrial building	2006
PL5CIP	Cast-in-place piles	Onsite reuse	Office building	2018
PL6CIP	Cast-in-place piles	Repurposing	Shallow foundation, Observatory	2019
RF1	Parts of the foundation plate as floor slabs	Repurpose	Multi-residential building	1997
RF2	Cast-in-place foundation	Onsite reuse	Office building	2022
RF3	Mat foundation	Onsite reuse	Office building	2018
RF4	Mat foundation	Onsite reuse	Hotel	2019
RF5	Mat foundation	Repurpose	Storage	2022

PL = Pile foundation
RF = Raft foundation
PC = Precast

CIP = Cast-in-place
ST = Steel
T = Timber
*Only structural elements are mentioned.

6.4.1 Pile foundation

In parallel to the construction industry, deep foundations are significantly contributing to CO_2 emissions as well. The renovation and establishment of old buildings are most of the time concerned with the timber piles. However, the foundation reuse topic has transcended from timber pile reuse to steel and concrete piles along with differences in the using different construction materials, equipment, and techniques. The piles in the foundation that reach the EOL of the building lifecycle become almost impossible to remove from their current state and the entire sites need to be redeveloped. Even in the cases when piles are to be removed, they present a lot of difficulties and may even loosen the ground when pulled out again from their original place resulting in lowering the bearing capacity of adjacent newly placed piles. On top of that, these removed piles are disposed of and discarded as construction wastes (Tsubakihara Y, 2005). However, due to increased interest in the circular economy, there has been an increase in research toward developing new techniques to make pile foundations more sustainable through reuse.

In terms of closing the gap, taking waste products or products at the end of life from another industry could also be a possible approach in the case of piles. In the Shell Skyline project (PL1PC) the detailed process and challenges in terms of reuse of piles for old piles and compensating loads to new piles have been discussed using stochastic models and the results found from this project showed that the old foundation was able to carry the loads for the instalment of the new components (van Blijswijk, 2023). The triton square project aimed for outstanding classification in BREEAM, and this is one of the projects that successfully overcame challenges presented with the reusing of the foundation. The reuse of piled foundations in the Triton square project (PL2CIP) done by Arup, reuse of piled foundations contributed to approx. 25% of reused structure. Pile reuse has become an integral component in transitioning foundations towards circular economy principles.

Guidelines, testing and techniques

Various techniques and tools are being developed for the assessment of reusing the foundations and ensuring the safe design of the building. There are several non-destructive testing methods are currently available for the assessment of deep foundations such as parallel seismic test and impulse response (Sonic mobility) test (Hertlein & Walton, 2000). Radar scanning can assist with identifying the arrangement of type of the foundation. "CIRIA C653 Reuse of Foundation" is a publication for foundation design which introduces reuse load factors to assist in quantifying the opportunity for reuse (Astle et al., 2023).

Steel piles

The key factors contributing to the success of the Triton square project (F3P) were due to comprehensive record information available from the original construction and the integration of a 3D finite element model for estimating the performance of the new system (Tayler, 2020). One of the interesting case studies is for green piles where surplus steel pipe from the oil industry is used to make circular steel piles for building foundations (Addis, 2006). Similar to circular steel pipes, screw piles also show a promising potential for reusability. (Addis, 2006).

Most of the case studies found for the steel piles are for highway bridges, the testing methods, techniques, and concepts for the bridges suggest reuse as a viable option. Greenock Creek Bridge (F4P) was assessed to check if the existing steel pile foundations could carry the new superstructure load for another 75 years. Through various intensive geophysical tests and depending upon the guideline developed by the Ministry of Transportation, Ontario, Canada for reusing foundations, it was found that foundation reuse presented as a viable option.

Timber piles

The concept of pile reuse was first initially started with timber piles. In the case study for Tobacco Dock in London (Butcher et al., 2006) during the restoration of the project, the timber piles were dug out from the site which showed that the timber piles were completely unharmed from the environmental effects and presented a strong potential for reuse. Most of the wooden piles which are in waterlogged soils and not in contact with the exposed environment have shown long service life in a lot of historical sites.

These results can be seen much more clearly for historical bridges that are closer to waterfronts, rivers, and seas in several old towns such as Stockholm, Trondheim, and Amsterdam (Elam & Björdal, 2020). The key components that need to be present for a timber pile to function as intended are an interactive system of wooden foundation piles, surrounding soil matrix, and groundwater.

Concrete piles

In most residential and commercial projects, concrete pile foundations are the preferred method of construction due to their durability, versatility, and load-carrying capacity. There have been many studies and research done that showcase that reusing concrete piles have had a significant decrease in CO_2 emissions. In the case study for the Ochanomizu Sola City building (PL5CIP) a large redevelopment project of a 110m high-rise building, finished in 2013 used existing piles which were constructed in the 1980s.

The 169 existing bored piles were reused in combination with new 99 bored piles which led to a significant reduction of GHG emissions. In addition to this, the results of comprehensive investigations showed that the existing piles were serviceable and had sufficient bearing capacities and even the existing foundation slabs and pile caps were also reusable, based on the results of tests of the materials carried out for the concrete and steel. The challenges and barriers with the ongoing practices regarding the use of piles need a better framework and a proper assessment for the reuse of concrete piles. In recent years, a framework, risk assessment tools and design for protocol regarding the foundation reuse has been developed. In Figure 41, a summary of the protocol developed for the foundation reuse by Lim et al. (2023) for bridges. According to the report, foundation reuse needs to go through multiple stages and even selecting foundation reuse solutions depends on several methods and factors. The detailed flowcharts describing each state that show the necessary steps needed to be followed for the foundation reuse are shown in Appendix C. These protocols developed in detail for bridges could be discussed, adapted, and provided as a helpful tool as well for the foundation reuse of buildings.

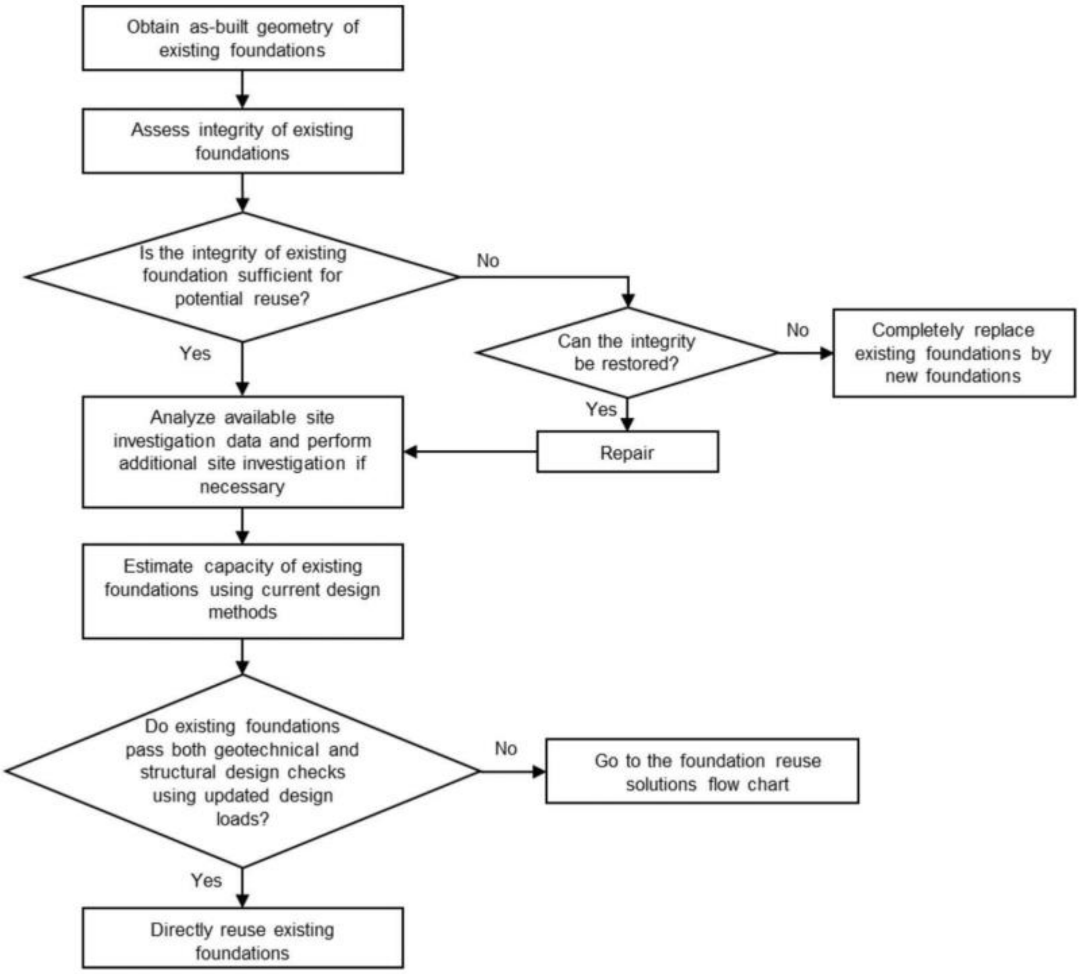


Figure 41. Framework of foundation reuse strategy. (Lim et al., 2023, p. 31)

Foundation reuse for bridges has become a well-established practice. According to the Deep Foundation Institute (DFI), bridges already have workshops, conferences, research reports and guidelines for foundation reuse. However, there have been very few cases of foundation reuse, particularly for buildings.

6.4.2 Shallow foundations

Shallow foundations can briefly be classified into isolated concrete foundations (CF) for single columns, combined CFs for several columns, and raft foundations for whole buildings (Pujadas-Gispert et al., 2018). In general, a foundation is classified as shallow, if the depth is less than its width. Mat and raft foundations are generally used to support structures like residential or commercial buildings where soil condition is poor, storage tanks, and silos foundations for heavy industrial equipment. The major impact from GHG emissions for a shallow foundation in the construction of a raft foundation for a high-rise residential building was for materials, equipment usage, and transportation respectively (Sandanayake et al., 2016). The reuse perspective of the shallow foundation must be researched more in detail, to seek probable approaches. Even though isolated CFs are a common foundation for frame structure, little literature has been found on them (Pujadas-Gispert et al., 2018).

Case studies

In one of the transformation projects, the Arup Television Centre in London UK (RF3), it was observed that reusing the existing foundation led to minimizing the embodied carbon and environmental impact. Similar to this another project from Arup was the Claridge Hotel (RF4) which included reusing the existing raft slab to create an additional 5500 m^2 of space (*Transform & Reuse*, 2020). Moreover, case study RF5 in detail described in chapter 6.2.1 as CIP4F, the cast-in-place concrete slabs were repurposed into an isolated column footing (bauburoinsitu, 2022).

The Lumi project (RF2) in Stockholm managed to reuse the entire foundation of an old office building from 1970. A new seven-storey office building was built with the reused foundation slab as basis. However, no technical details were shared for this project, limiting the possibility of learning from this project.

Repurposing of the foundation was tested in the Udden project (RF1) in the year 1997. Parts of the slab (30m^2) from a multi-residential building have been cut out and were reused as floor slabs in another multi-residential building. However, no technical report exists for the project and therefore it can only be cited as an example without having informative value.

Research outcomes

Reusability has a greater impact than recycling as previously discussed many times (Gorgolewski, 2017). As per the author's knowledge, the case studies found for the reuse of shallow foundations were limited. Especially in the growing urban environment, it implies that foundation reuse will lead to the reduction of the environmental impact of buildings. The current practises for foundations that are developed in the building industry involve the reduction of material and energy use. Although there have been several developments for guidelines for pile foundations, much focus seems to be missing for shallow foundations. The use of shallow foundations is prominent in the case of residential buildings. The shallow foundation is not designed to lower its environmental impact. In the case of growing cities where the buildings are evolving, the old foundation from the previous could be reused to further develop the plants.

There have been several cases such as RF3 and RF4, where reusing the existing raft slab during expansion of the building resulted in a significant reduction of the environmental impact of the building. New approaches, guidelines and regulations need to be developed and further research should be taken to adapt foundations according to the concept of CE principles.

7 Discussion

In this chapter, the results and findings from this study are discussed. This includes the individual elements in their respective construction types as well as the material-related aspects. The analysis of the various elements reveals differences between the elements with respect to the feasibility of CE strategies. Conducting the literature review, which involves studying the case studies and pilot projects, shows the varying suitability and potential of the elements for the respective CE strategies. The results and insights gained are used to elaborate on the individual elements and construction types within the CE framework employed in this study. The elements are evaluated for their applicability to the selected CE strategies and the current research status of the element regarding circular economy is assessed. For each construction type, an overview of the technical challenges and opportunities regarding the application of CE strategies is provided in the form of keywords.

In Table 16, Table 17 and Table 18, summaries of the technical details for the studied building elements and their respective construction types are provided. The "+" category covers findings, tools, and guides that positively influence the circularity of the respective elements, as well as promising case studies. In contrast, the "–" category summarizes factors and challenges that hinder or complicate the application of CE strategies for these elements. Additionally, Table 15 illustrates the allocation of case studies for each element across the various study types. These results are elaborated on in more detail within the discussion of the elements. Based on the combined findings from tables 15-18, the circularity, current and potential, of the various elements is evaluated and compared.

Table 15. Amount of case studies for each element type with distinction into the CE strategies.

Element	Element type	**Case studies**			
		Element reuse	Material reuse		Inventory analysis / Theoretical design
			Repurpose	Remanufacturing	
Floor slabs	CIP	1	2	1	1
	HCS	4	-	-	2
	CLT	-	-	5	1
	Glulam	4	-	2	1
Load-bearing walls	CIP	2	2	-	2
	Precast	6	-	-	4
	CLT	1	-	5	1
Foundations	Deep	5	1	-	-
	Shallow	3	2	-	-

7.1 Base materials

The material-specific investigation of timber and concrete elements in chapter 6.1 show the general technical and systematic barriers regarding the implementation of CE strategies for structural elements. These challenges are discussed in the following section.

Concrete

As Suchorzewski et al. (2023) states, "durability and assessment of remaining service-life are the main technical challenges to the reuse of structural concrete elements". However, various laboratory studies and projects demonstrate that the residual service life of concrete elements is often sufficient for reuse in load-bearing functions. A major issue, though, is the uncertainty associated with determining the mechanical performance of aged concrete elements through non-destructive testing. This complicates the recovery process, as significant efforts may be invested in elements that, after extensive post-deconstruction testing, are deemed unsuitable for reuse. At this stage, CE strategies related to material reuse become valuable alternatives for extending the lifespan of these elements. This makes the examination of elements more appealing to involved parties, as multiple forms of reuse become possible. While concrete recycling is already well explored and applied in several pilot projects, the absence of end-of-waste criteria and the limited availability of standards for the recycling process and RAC reduce its applicability for structural elements.

The tool from Nebest offers a more straightforward and structured approach to exploring circular economy (CE) possibilities for structural concrete elements. Additionally, the calculation tool and classification system developed by RISE represent significant progress towards CE certification of reclaimed concrete elements. These tools provide a scientifically validated method to evaluate, classify, and label recovered concrete elements based on their durability, physical condition, and residual lifespan.

Timber

The popular cascading concept in timber recognizes that aged timber has a limited range of reapplications due to degradation and alterations from its previous service life. The goal of this concept is to keep wooden products in high-value applications for as long as possible. The primary concern with aged timber is its mechanical properties, which are more challenging to control compared to concrete, given that wood is a natural material with variable quality. However, analysed studies suggest that ageing effects are of secondary importance. The loading history and the original quality of the timber elements are the main influencing factors. This impacts grading results, as visual grading often rejects most reclaimed timber elements. Nonetheless, non-destructive testing has shown that many of these elements still possess high-strength qualities, making them suitable for structural applications. The InFutUReWood research project proposes a probabilistic piece-by-piece grading system for reclaimed timber. This system, though, deals with reduced certainty regarding mechanical properties and recommends conservative design values for load-bearing timber structures. Moreover, the adoption of a new grading system will require significant time, involving extensive testing and considerable investments in manufacturing infrastructure.

The introduction of the Norwegian standard for reclaimed timber marks a significant milestone in the circularity of timber elements. Although not tailored specifically for structural elements, the standard offers valuable insights, methodologies, and quality criteria for reclaimed timber. Even for projects outside of Norway, this standard can serve as a guiding principle for contractors and a reference point for the establishment of standards elsewhere. Standards not only establish uniform guidelines and processes, ensuring compatibility within the industry but also enhance the credibility of circular timber elements.

7.2 Floor slabs

Based on Table 16 the floor slab elements are evaluated and compared with each other to conclude the suitability and feasibility of each CE strategy. The number of case studies for CIP floor slabs within this study is limited for each CE strategy. Hence, it is important to interpret statements with caution. Nonetheless, the insights concerning digital tools and connection details are significant and can be utilized in circular construction projects. The utilization of 3D units and piecewise repurposing are recognized as valuable methods and viable alternatives for the challenging recovery of CIP floor elements. The scarcity of case studies for CIP floor slabs might be attributed to the challenges involved in extracting individual elements from a monolithic slab. The limited number of case studies does not allow for a definitive conclusion regarding the most suitable CE strategy, but it has shown promising results for each of the strategies. The availability of various digital tools, including the determination of reuse potential, structural feasibility, and residual life expectancy, enables contractors and involved parties to explore the circularity of CIP floor slabs in a more defined and trustworthy way.

The case studies relevant to HCSs exclusively emphasize reuse through pilot projects and theoretical examinations. The modularity of prefabricated HCS elements contributes to heightened recovery rates and minimal dimensional loss. The established reuse standard from Norway represents a significant milestone for the circularity of HCS floor elements. If this standard were to be adopted as a guiding principle in other countries, it has the potential to enhance the efficiency and recognition of the reuse process. Regrettably, no case studies about the remanufacturing and repurposing of HCS elements were uncovered. This absence may be attributed to the lightweight nature of the elements, rendering them unsuitable for use as or within other elements. This suggests that reusing HCS floor elements is the most effective option for enhancing circularity. However, HCS elements deemed unsuitable for reuse as whole elements should be further investigated for circular strategies. Since the use of RAC in structural elements requires high-quality parent concrete, the rejected HCS elements could serve as a valuable source for this purpose.

CLT and glulam floor slabs, both timber elements, show similar performance across various aspects. Both types demonstrate high recovery rates and the potential to be manufactured from reclaimed timber. This potential can be significantly improved with the release of a standard for reclaimed timber that defines quality criteria and the introduction of a proposed grading system for reclaimed wood developed by InFutUReWood.

Therefore, manufacturing CLT and glulam from secondary low-grade timber, as well as future remanufacturing of deconstructed CLT and glulam elements into new ones, appears to be a viable approach to enhance the circularity of these structural elements.

Based on the reference reuse scenario for CLT and glulam from the French wood industry, it can be concluded that CLT is more susceptible to dimension losses during deconstruction. However, CLT is overall more standardized than glulam elements. While the total number of case studies for both elements is almost identical, the focus of the individual case studies varies. For glulam, out of seven case studies, four are pilot projects featuring the reuse of structural glulam elements, while the other three studied remanufacturing and site analyses. For CLT, on the other hand, no pilot projects for structural floor elements were found, and most of the case studies involved laboratory studies for remanufacturing. The difference in the case studies of these elements, despite their similar composition, can be attributed to their commercial histories. CLT has only been in use in Europe since the early 2000s, meaning that multi-storey CLT buildings have not yet faced demolition. In contrast, glulam has been used since the early 1900s, resulting in the demolition of many buildings with glulam structures and enabling the exploration and execution of glulam reuse. Nonetheless, CLT elements should be investigated for potential element reuse before a significant number of CLT-based buildings reach their end-of-life. Circularity strategies for CLT elements must be identified and established by that time.

Neither element has been extensively explored for repurposing. For CLT, the limited exploration can be explained by the fact that CLT elements have not consistently reached their end-of-life, same as for reuse. This suggests that, at present, the circularity of CLT floor elements can be enhanced by remanufacturing secondary timber into CLT. However, given the results of site analyses, as well as the modular form and standardized dimensions—both aspects comparable to HCS elements—the potential for element reuse and repurposing is expected to be significant. Especially since the composition of structural CLT floor and wall elements does not differ, both elements may be well-suited for repurposing. For instance, a floor slab element with too small a span after deconstruction may still be suitable as a wall element, provided it is structurally sound. In contrast, glulam floor structures, which mainly consist of beams or portal frames, have more limited options for repurposing into other structural elements. Therefore, for glulam, element reuse and remanufacturing should be prioritized as the main CE strategies, while for CLT additionally repurposing seems like a viable option.

Table 16. Overview of technical challenges and potential solutions for floor slabs.

Floor slabs				
	CIP	HCS	CLT	Glulam
+	▪ Sawing pattern for reuse available ▪ Digital tools for reuse potential and redesign ▪ Reuse in 3D units ▪ Detailed reused element connections ▪ Piecewise repurposing	▪ Modular character enhances recovery rates ▪ Deconstruction has minimal effect on element dimensions ▪ Numerous pilot projects for HCS reuse Standard for reuse exists ▪ Detailed connections for reused elements	▪ High recovery rates ▪ Standard for reclaimed timber exists ▪ CLT production using new and reclaimed timber performs well ▪ New grading system for timber proposed ▪ Reference reuse scenario as orientation ▪ Analytical models for property prediction for CLST	▪ High recovery rates ▪ Standard for reclaimed timber exists ▪ Glulam production with reclaimed timber successful ▪ Reuse potential assessment mind map available ▪ New grading system for timber proposed ▪ Reference reuse scenario as orientation
-	▪ Undefined connections lead to complex recovery for reuse ▪ Circularity is challenging due to the monolithic structure ▪ Limited case studies	▪ Reused HCSs require enhancement for sound and fire requirements ▪ Lightweight nature limits opportunities for repurposing or remanufacturing	▪ Deconstruction reduces element dimensions ▪ Current grading system for new timber rejects most reclaimed timber ▪ Limited case studies	▪ Varied sizes and connections ▪ Grading system for new timber rejects reclaimed timber ▪ Limited case studies

7.3 Load-bearing walls

Table 17 provides an overview of technical hurdles and positive findings for load-bearing walls, divided into the various element types. The circularity of CIP walls is predominantly influenced by the material concrete, with less emphasis on its form and construction. Consequently, many considerations for CIP wall elements align with those for CIP floor slabs. Particularly noteworthy is the challenge posed by the monolithic structure with undefined connection areas. While the case study CIP1W involved the reuse of a CIP wall element in its entirety, the lack of technical details and the age of the project, conducted in 1997, raise doubts about its current relevance. Therefore, reuse in the form of 3D units or block-wise repurposing may be more feasible options than reusing individual wall elements. The available two-step reusability assessment as well as the tools and methods presented in the concrete chapter 6.1.1 ease the inventory and evaluation process, thereby providing practical means for contractors.

The modularity of precast wall elements increases their recovery rate, making them more suitable for reuse. This is evident in the case study overview in Table 15, where reuse comprises 60% of the examined precast wall projects. Furthermore, the four theoretical studies also focus on element-wise reuse. However, aside from the theoretical studies, the reuse projects date back to 2010 and earlier, with no implemented precast wall reuse since then. This seems contradictory given the increased awareness of sustainable construction practices in recent years. Compared to HCS elements, which serve as representatives for precast floor slabs and have seen increasing reuse over the past three years, the lack of a standard, guideline, or reference cases for precast walls is a significant differentiating factor. Nonetheless, element reuse can be seen as the most desirable option for precast wall elements.

While a reference scenario exists for CLT wall elements, no practical implementations have been observed, like the situation with CLT floor elements. However, the production of CLT elements from secondary timber demonstrates comparable performance to those made from new timber. The analytical model from the Canadian CLT handbook offers reliable predictions of CLST properties. Further research in this area could reduce the amount of testing required for these elements, thereby decreasing production time and costs, and enhancing feasibility. From a construction perspective, CLT wall and floor elements are identical, but inventory analyses conducted in France revealed differing recovery rates. This discrepancy is partly due to the cutting of connections, which leads to greater dimension losses for wall elements. Additionally, the height criteria for wall elements, which must ensure sufficient room height when reapplied, significantly impact their recovery rates. Therefore, the restriction on reuse is not solely related to the composition and geometry of the elements but also their function. This is particularly true for wall elements, as opposed to floor elements, which can be arranged according to the available element span to some extent. Load-bearing walls, however, cannot be reduced in height without resulting in insufficient room height, posing a significant challenge for their reuse. One potential solution to increase the recovery rate in future buildings is to establish a standard minimum height of three meters for CLT wall elements. This would help minimize the use of shorter, individualized components.

Table 17. Overview of technical challenges and potential solutions for load-bearing walls.

	Load-bearing walls		
	CIP	Precast	CLT
+	▪ Two-step reusability assessment available ▪ Reuse in 3D units ▪ Detailed reused element connections ▪ Piecewise repurposing ▪ Subsequent installation of post-tension cables explored	▪ Modular character enhances recovery rates ▪ Numerous case studies for reuse, but mostly older projects or theoretical ▪ Optimized designs for reclaimed elements explored ▪ Detailed connections for reused elements	▪ Intermediate recovery rates ▪ Standard for reclaimed timber exists ▪ CLT production using new and reclaimed timber performs well ▪ New grading system proposed ▪ Reference reuse scenario as orientation ▪ Analytical models for property prediction for CLST
-	▪ Circularity is challenging due to the monolithic structure ▪ Undefined connections lead to complex recovery for reuse ▪ Limited case studies	▪ Limited case studies for repurposing and remanufacturing ▪ No guidelines or standards available	▪ Deconstruction reduces element dimensions ▪ Current grading system for new timber rejects most reclaimed timber ▪ Limited case studies

7.4 Foundations

In Table 18 the beneficial and disadvantageous factors of deep and shallow foundations are presented. In recent years, several reuse projects for deep or pile foundations have been completed, as illustrated in Table 18. In these cases, the piles were reused onsite, remaining in the ground, and being reused as part of the new structure. A framework for foundation reuse was established, providing guidelines to assess the suitability of existing foundations for such purposes. Additionally, a brief guide for foundation reuse was published, featuring a conceptual risk assessment tool. This tool, combined with load factors, classifies foundations into various risk categories.

The comprehensive framework for reusing existing foundations, initially developed for bridges, could be adapted for buildings, given that most parameters influencing the foundations of both construction types are similar.

Several case studies on the reuse and repurposing of shallow foundations were found. However, the absence of theoretical analysis or conceptual research means that there are no established guidelines or standardized processes. This likely increases the difficulty of implementing circular economy strategies and reduces the number of projects exploring the potential reuse or repurposing of existing shallow foundations. Furthermore, due to the still relatively limited number of case studies and the absence of technical reports in many instances, it is challenging to make accurate assessments. A notable trend observed with foundations is the distribution of keywords indicating positive and negative aspects. Unlike other elements where the number of positive keywords outweighs the negatives, this balance is not as evident for deep and shallow foundations. This could be attributed to the inherent difficulty in enhancing the circularity of foundations, as well as the lack of research dedicated to this specific building element.

Table 18. Overview of technical challenges and potential solutions for foundations.

Foundations		
	Deep	Shallow
+	▪ Numerous case studies for pile reuse ▪ Reuse guide and protocol exists ▪ Risk assessment tool available	▪ Increasing number of case studies for reuse ▪ Repurposing of cut-out blocks
-	▪ Extraction of piles results in damage to elements and disrupts soil ▪ Limited case studies for repurposing and remanufacturing	▪ No conceptual research for CE strategies ▪ Poor documentation of pilot projects ▪ No guidelines or standards available ▪ Limited case studies for repurposing and remanufacturing

8 Conclusion and recommendations

The study aims to investigate circular strategies for the structural building elements and is stated in section 2.1. In order to reach this objective three research questions have been listed as follows and answered in serial order.

8.1 Conclusions

Research question 1:
What are the most significant environmental contributors in multi-family buildings?

The hotspot analysis results indicate that structural building elements account for 70% of the total GWP/BTA impact for an average Swedish multi-residential building, highlighting their significant contribution to the carbon footprint of residential buildings. Floor slabs, contributing 33%, are the largest single contributor. Further analysis revealed considerable variability in the GWP/BTA figures for floor slabs, due to different element types. Load-bearing interior and exterior walls follow, contributing 14% and 11%, respectively. While exterior walls show broad variations in GWP/BTA values, interior wall types exhibit more uniform behaviour. Foundation plates, initially expected to be major contributors, account for only 5% of the total GWP, which is relatively small compared to other elements.

Research question 2:
What are possible CE strategies for building elements with high environmental impact?

Structural building elements are the largest contributors to the environmental impact of multi-residential buildings. While various frameworks for CE strategies exist, they are rarely specifically tailored for buildings. This study investigates three CE strategies: element reuse, material reuse, and recycling. Recycling is included for complementary reasons. Element reuse, which can be either onsite or offsite, involves reusing the elements in their original function without significant alterations to their geometry or composition. However, due to their previous life cycle, damages, wear, and modifications can influence the mechanical properties of the elements. Repairs and reinforcement may be necessary for the elements to be reused in a structural function.

Materials reuse, repurposing and remanufacturing, are often considered less desirable CE strategies compared to element reuse. However, the study demonstrates that material reuse can not only be an equally viable alternative for elements like CLT and glulam but is also crucial for elements rejected in the element reuse process.

While recycling is a prominent topic in the building sector, other circular strategies like reuse, repurposing, and remanufacturing are currently neglected. Furthermore, recycling often occurs at the material level, with materials mostly being downcycled, such as timber into particleboards and concrete crushed for road filling. Therefore, element and material reuse of existing products should be preferred over recycling.

The main concern with element and material reuse is the durability of the aged elements. Several case studies and pilot projects have revealed that reclaimed concrete and timber elements still possess sufficient mechanical performance and residual lifetime to be reused. However, the lack of standards, guidelines, and in the case of timber, an adapted grading system significantly increases the difficulty and complexity of implementing CE strategies.

Research question 3:
How element types influence the circular potential of structural elements?

The analysis indicates that different strategies are suitable for various elements. For deep and shallow foundations, onsite element reuse appears to be the most feasible circular option, primarily due to the highly challenging recovery process for piles and foundation plates. Reusing elements offsite is very difficult because piles are vulnerable to damage during extraction, and their length makes transportation to other sites challenging. Therefore, pile foundations should primarily be considered for onsite element reuse. The in-situ cast nature of foundation slabs presents several challenges regarding circularity. The undefined connection areas and highly individualized reinforcement layouts make extracting usable elements from the slab difficult. While case studies for material reuse exist, their limited number prevents drawing meaningful conclusions.
The same observation applies to CIP floor and wall elements. Additionally, studies and projects on element reuse for these components are rather limited. The primary issues are the uncertainty of disturbing the structural integrity and the force-locked reconnection of the elements. While the limited number of case studies prevents a definitive conclusion on the most suitable circular economy strategy, the results for each strategy have been promising.

Prefabricated elements such as HCS, precast walls, CLT floor and wall elements, and glulam demonstrate great suitability for element reuse. Their modular form proves to be beneficial, resulting in improved recovery rates. The defined connection areas and clear element outlines, along with their design for lifting during construction, reduce the complexity of the deconstruction process. Extensive investigations in pilot projects and theoretical studies have been conducted on the reuse of most of these prefabricated elements. Except for CLT, which is relatively new as a commercial building element and has not consistently reached its EOL, resulting in a lack of available pilot projects. However, comprehensive site analyses indicate promising recovery rates for CLT wall and floor elements. Regarding material reuse, prefabricated timber elements, including CLT and glulam, have been extensively investigated for remanufacturing. The utilization of low-grade secondary timber, sourced from demolished buildings, in CLT and glulam elements shows comparable performance to new elements, offering an equally viable circular option for structural timber elements. Unexpectedly, CLT elements have not been thoroughly investigated for repurposing. The identical composition of wall and floor elements makes it reasonable to repurpose, for instance, floor elements with insufficient spans into wall elements.

No case studies are available for remanufacturing or repurposing precast concrete elements. The absence of such studies for HCS floor elements might be attributed to their lightweight structure, making it challenging to repurpose them or reassemble them into new HCS elements. However, precast wall elements may offer potential applications for material reuse, such as the exchangeability of prefabricated concrete floor and wall elements.

General conclusions
Referencing Receiver
Building

Figure 13, the process from donor to receiver remains identical regardless of the initially planned CE strategy. However, when examining the CE strategies and structural elements, it becomes clear that each step in this process can significantly influence the suitability of the CE strategies for a given element. Step 1, the inventory analysis, can disqualify structural parts for element reuse if the visual inspection reveals damages or geometrical irregularities from previous use. Additionally, the results from non-destructive testing in step 2 may indicate a low residual service life or other performance issues, which could rule out both element and material reuse. Deconstruction is repeatedly emphasized as a critical phase for reclaimed elements due to the high potential for damage during the process. Damages to otherwise suitable and high-performing elements could render them unfit for the planned CE strategy. The extensive testing of the elements in their dismantled state in step 4 could lead to the rejection of elements initially graded as reusable if issues regarding mechanical performance or durability are discovered. This can include microcracks, damage to the reinforcement, or the ingress of harmful substances. Even if repair and modification of the elements are technically feasible, they may be rejected for economic or environmental reasons. The latter could occur if too much additional material is needed to restore the elements for their new intended function. Connecting reused elements at the new site can also pose several challenges regarding dimensional deviations or load transfer. Ensuring precise alignment is critical, as even minor discrepancies in dimensions can lead to significant structural issues. This precision is difficult to achieve with reclaimed elements, which may have deformations or variations from their original specifications due to previous use or damage during deconstruction. Moreover, the load transfer between reclaimed elements and new construction materials can be problematic. Reused elements may not have been designed for the new load paths and stress distributions encountered in the new configuration.

Implementing CE strategies for structural building elements presents numerous and varied technical challenges. Constructing with reused elements demands additional planning and construction effort, as these elements often have smaller and non-standardized dimensions due to demolition. In practical terms, this translates to reduced flexibility, as more load-bearing walls or columns are needed to compensate for the smaller spans and widths of reused elements. In summary, while designing with reclaimed elements offers significant sustainability benefits, it requires meticulous planning, precise execution, and often innovative engineering solutions to address the inherent challenges. Moreover, many

projects conducted by contractors and companies provide only limited or non-technical information about the process and challenges encountered.
This lack of detailed information limits the value of insights and knowledge necessary for the development of CE strategies for structural building elements. Successful transition from a linear to a circular economy requires collaboration and knowledge-sharing.

8.2 Future Research Direction

This research can be used to further initiate the consideration for adapting circular strategies for reducing environmental impact. The research shows an overview of the design approaches, tools and techniques through case studies and pilot projects for finding circular strategies most applicable to each structural element. This chapter discusses recommendations and potential future research directions.

- The dataset included only 16 LCA project data which limited the scope of the research. It is recommended to use a larger in-depth LCA database to expand the research. This will lead to a more representative dataset for the building category and aid in investigating further the contributions of the major structural elements to the GWP.
- In contrast to showing major contribution from the foundation, due to its massive volume in the building. There have been not many initiatives regarding the reuse of the foundation. The foundation reuse shows a promising impact in the reduction of GHG emissions from the entire building. Even though, many risk assessment tools and reuse frameworks have shown benefits of turning building foundations in circular paths. There still exist considerable challenges and barriers to circular building foundations. It is recommended that more discussions and research be forwarded for foundation reuse.

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Appendix

A – Overview case studies

In Appendix A, a detailed overview of the case studies is provided in the form of tables. These were found through searching on the internet and literature. For better understanding, the tables are divided as per the building elements floor slabs, load-bearing walls and foundations in Table 19,Table 20 & Table 21 respectively.

Floor slabs

Table 19. Detailed overview of case studies and pilot projects involving floor slabs

Code	Details to elements*	Type of study	Building type	Date	Location	Source
CIP1F	Cast-in-place concrete	Inventory analysis	Office building	2022	Sweden	(Ackebo & Wall, 2023; Vasakronan AB, n.d.; White Arkitekter Sverige, n.d.)
CIP2F	In-situ concrete	Onsite reuse	Multi-residential building to single-family house	2019	Netherlands	(Elma Durmisevic, 2019)
CIP3F	In-situ concrete	Repurposing	Parking pavement	2021	Switzerland	(Küpfer et al., 2022)
CIP4F	In-situ concrete	Remanufacturing	Storage building	2022	Switzerland	(bauburoinsitu, 2022)
CIP5F	Cast-in-place walls	Repurposing	Basement wall to footbridge prototype	2021	Switzerland	(Küpfer et al., 2022)
HCS1	Hollow core slabs	Offsite reuse	Office building	2021	Norway	(Entra ASA, 2021)
HCS2	Hollow core slabs	Onsite reuse	Parking garage to office building	2021	Sweden	(Fabege, n.d.; Suchorzewski et al., 2023)

Code	Details to elements*	Type of study	Building type	Date	Location	Source
HCS3	Hollow core slabs	Inventory analysis	Office and warehouse	2021	Sweden	(Ackebo & Wall, 2023, p. 3; *Halverad Klimatpåverkan i Innovationsprojektet Parkhuset*, n.d.)
HCS4	Hollow core slabs	Inventory analysis	Office building	asm. 2021	Sweden	(Ackebo & Wall, 2023)
HCS5	Hollow-core slabs	Offsite reuse	Warehouse to residential building	2024	Sweden	(Framtiden Byggutveckling AB, 2024)
HCS6	Hollow-core slabs	Offsite reuse	Multi-residential to office building	2023	Sweden	(Skanska, n.d.; Skanska et al., n.d.)
CLT1F	CLT floor panels,	Inventory analysis, LCA study	-	2022	France	(Vial & Mandrara, 2022)
CLT2	CLT panels	Remanufacturing, Lab study	-	2024	UK	(Dong et al., 2024)
CLT3	CLT panels	Remanufacturing, Lab study	-	2023	Ireland	(Chúláin et al., 2023)
CLT4	CLT panels	Remanufacturing, Lab study	-	2023	Spain	(Llana, González-Alegre, et al., 2023)
CLT5	CLT panels	Remanufacturing, Lab study	-	2018	UK	(Rose et al., 2018)
CLT6	CLT panels	Remanufacturing, Lab study	-	2021	Norway	(Stenstad et al., 2021)
G1	Glulam beams	Inventory analysis, LCA study	-	2022	France	(Vial & Mandrara, 2022)

Code	Details to elements*	Type of study	Building type	Date	Location	Source
G2	Glulam timber frame	Offsite reuse	Ice rink hall	2019	France	(Vial & Mandrara, 2022)
G3	Glulam	Onsite reuse	Office building	1996	Canada	(Addis, 2006, p. 31)
G4	Glulam timber frame	Reuse, Laboratory study	Textile factory	2023	France	(Yahmi et al., 2023)
G5	Glulam timber frame	Onsite reuse	Industrial hall	2024	France	(Atelier du Pont Architects, n.d.; Vial & Mandrara, 2022)
CIP = Cast-in-place HCS = Hollow-core slabs CLT = Cross-laminated timber G = Glulam F = Floor slab (addition to distinguish between floor and wall elements made from the same material) *Only structural elements are mentioned.						

Load-bearing walls

Table 20. Detailed overview of case studies and pilot projects involving load-bearing walls

Code	Details to elements*	Type of study	Building type	Date	Location	Source
CIP1W	Cast-in-place walls	Offsite reuse	Multi-residential building	1997	Sweden	(Addis, 2006; Eklund et al., 2003)
CIP2W	Cast-in-place	Onsite reuse	Residential building	2019	Netherlands	(Elma Durmisevic, 2019)
CIP3W	Cast-in-place	Repurposing	Basement wall to footbridge prototype	2021	Switzerland	(Küpfer et al., 2022)
CIP4W	Cast-in-place walls	Inventory analysis	Multi-residential building	2023	Switzerland	(Devènes, Bastien-Masse, Küpfer, et al., 2023)

Code	Details to elements*	Type of study	Building type	Date	Location	Source
CIP5W	Cast-in-place walls	Theoretical onsite reuse	Storage building	2024	Switzerland	(Widmer et al., 2023)
			Multi-residential building			
			Residential building			
CIP6W	Cast-in-place walls	Repurposing	Parking pavement	2021	Switzerland	(Küpfer et al., 2022)
PC1W	Precast system wall panels	Onsite reuse	Multi-residential building	2005	Germany	(Huuhka et al., 2019)
PC2W	Precast system wall panels	Offsite reuse	Multi-residential building	1986	Netherlands	(Huuhka et al., 2019)
PC3W	Precast walls, inner + outer	Offsite reuse	Residential building	2001	Germany	(Dechantsreiter et al., 2015)
PC4W	Precast walls	Thesis - Theoretical offsite reuse	Multi-residential building	2020	Netherlands	(G.J. van den Brink, 2020)
PC5W	Precast walls, slabs, beams	Thesis - Connection design for reused elements	-	2019	Netherlands	(Volkov, 2019)
PC6W	Precast walls, slabs, beams, columns	Thesis - Theoretical offsite reuse	Multi-residential building	2013	Netherlands	(Glias, 2013)
PC7W	Precast wall panels, inner + outer	Offsite reuse	Prototype	2010	Germany	(Dechantsreiter et al., 2015; zukunftsgeraeusche, 2011)
PC8W	Precast structural frame	Offsite reuse	Multi-residential building	2008	Germany	(Huber, 2019; zukunftsgeraeusche, 2008)

Code	Details to elements*	Type of study	Building type	Date	Location	Source
PC9W	Precast system wall panels	Offsite reuse	Prototype	2004	Germany	(Kozminska, 2019; zukunftsgeraeusche, 2011)
PC10W	Precast walls, inner + outer	Planned offsite reuse	Community centre	Planned for 2024/2025	Germany	(Henschel, 2023)
CLT1W	CLT Wall panels (3x6m)	Offsite reuse	Prototype	2016	Japan	(Passarelli, 2018)
CLT2W	CLT wall panels	Data collection, LCA study	-	2022	France	(Vial & Mandrara, 2022)
CIP = Cast-in-place PC = Precast CLT = Cross-laminated timber W = Wall (addition to distinguish between floor and wall elements made from the same material) *Only structural elements are mentioned.						

Foundations

Table 21. Detailed overview of case studies and pilot projects involving foundations

Code	Details to elements*	Type of study	Building type	Date	Location	Source
PL1PC	Pile foundation Precast concrete piles	Onsite reuse	Chemical plant	2023	Netherland	(van Blijswijk, 2023)
PL2CIP	Pile foundation	Onsite reuse	Mix-used commercial building	2022	London	(Tayler, 2020)
PL3ST	Pile foundation (steel)	Onsite reuse	Bridge	2023	Canada	(Sangiuliano et al., 2023)
PL4T	Timber piles	Onsite reuse	Industrial building	2006	UK	(Addis, 2006, p. 96; Butcher et al., 2006)

Code	Details to elements*	Type of study	Building type	Date	Location	Source
PL5CIP	Cast-in-place piles	Onsite reuse	Office building	2018	Japan	(Watanabe et al., 2016)
PL6CIP	Cast-in-place piles	Repurposing	Shallow foundation, Observatory	2019	Sweden	(NCC, n.d.)
RF1	Parts of the foundation plate as floor slabs	Offsite reuse	Multi-residential building	1997	Sweden	(Eklund et al., 2003)
RF2	Cast-in-place foundation	Onsite reuse	Office building	2022	Sweden	(Vasakronan AB, n.d.; White Arkitekter Sverige, n.d.)
RF3	Mat foundation	Onsite reuse	Office building	2018	UK	(*Transform & Reuse*, 2020)
RF4	Mat foundation	Onsite reuse	Hotel	2019	UK	(*Transform & Reuse*, 2020)
RF5	Mat foundation	Remanufacturing	Storage	2022	Switzerland	(bauburoinsitu, 2022)

PL = Pile foundation
RF = Raft foundation
PC = Precast
CIP = Cast-in-place
ST = Steel
T = Timber
*Only structural elements are mentioned.

B – Glulam on-site assessment mind map

In Appendix B, the detailed mind maps for glulam assessment, Figure 32, are shown. These mind maps are for evaluating cracks, insects attack and discolouration.

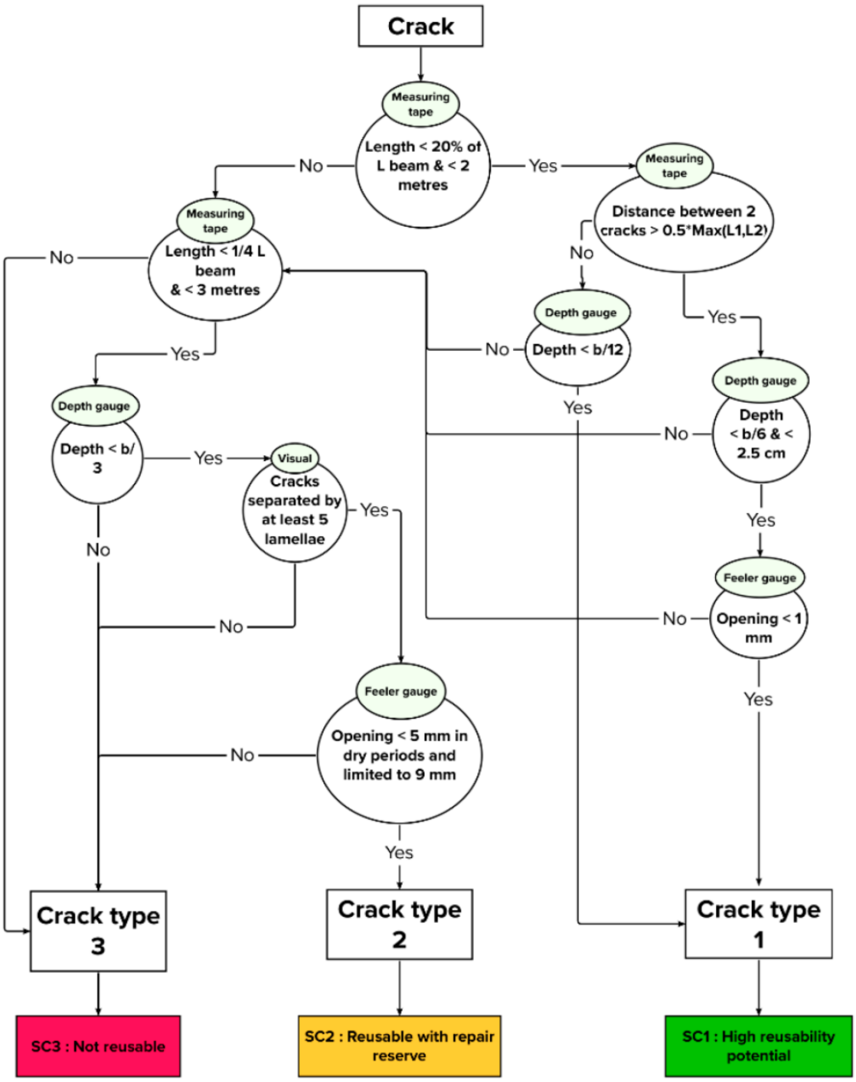

Figure 42. Crack mind map methodology. SC stands for Scenario Crack (Yahmi et al., 2023).

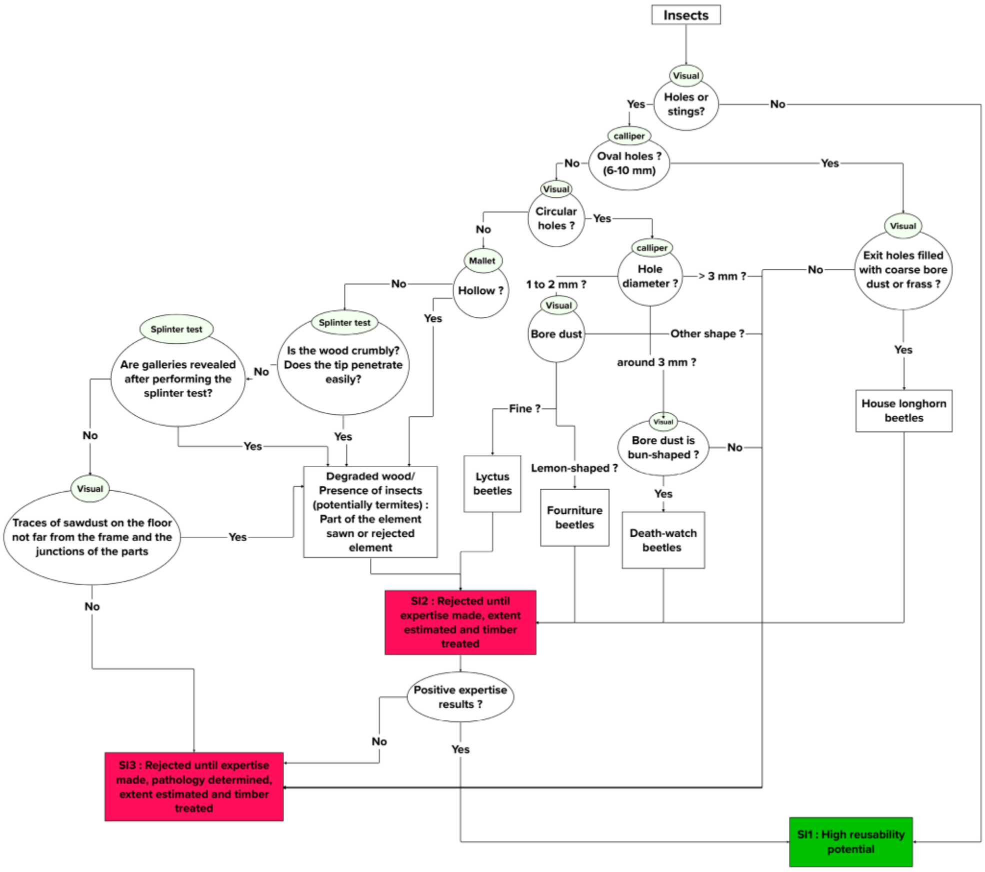

Figure 43. Insect mind map methodology. SI stands for Scenario Insect (Yahmi et al., 2023).

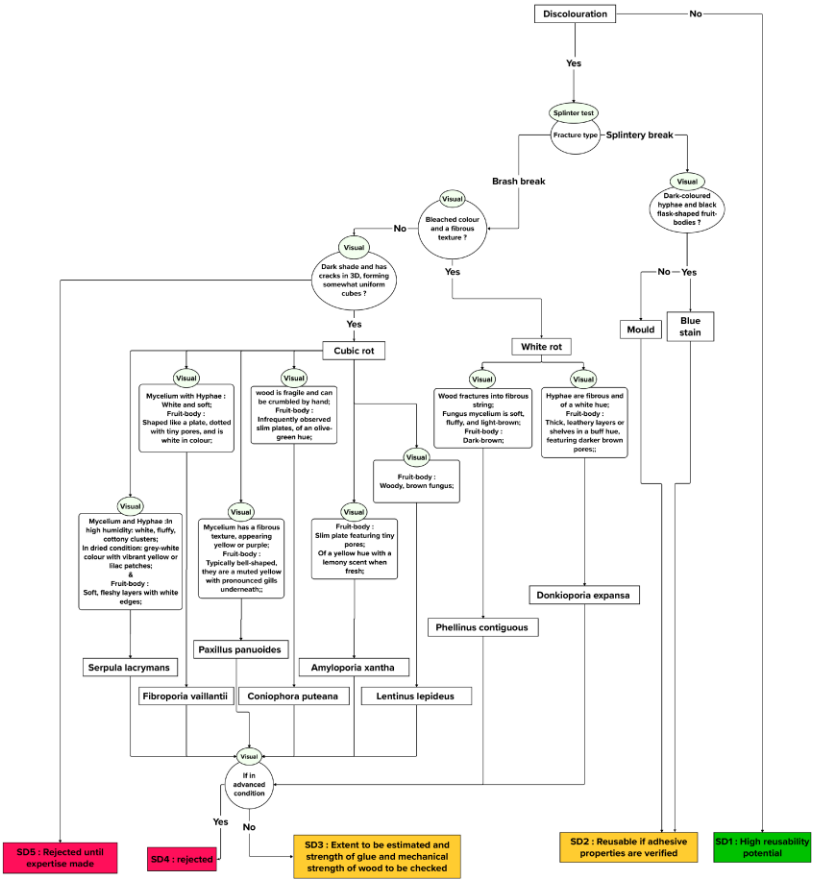

Figure 44. Discolouration mind map methodology. SD stands for Scenario Discolouration (Yahmi et al., 2023).

C – Protocol for foundation reuse

This appendix refers to show in detail about the protocols developed for the foundation reuse in bridges. The following flow charts show the step-by-step process needed to be followed to conclude the final foundation reuse solutions. The first part of the protocol starts with four flowcharts shown in

Figure 45,

Figure 46,

Figure 47 &

Figure 48 which inspects the existing foundation condition along with structural integrity by checking the unknown geometry, assessment of the material properties and assessing the defects in foundations.

Figure 49 shows second part of protocol where capacity of foundations is assessed. Lastly,

Figure 50 shows the final flowchart showing the processes to conclude selection of foundation reuse solutions.

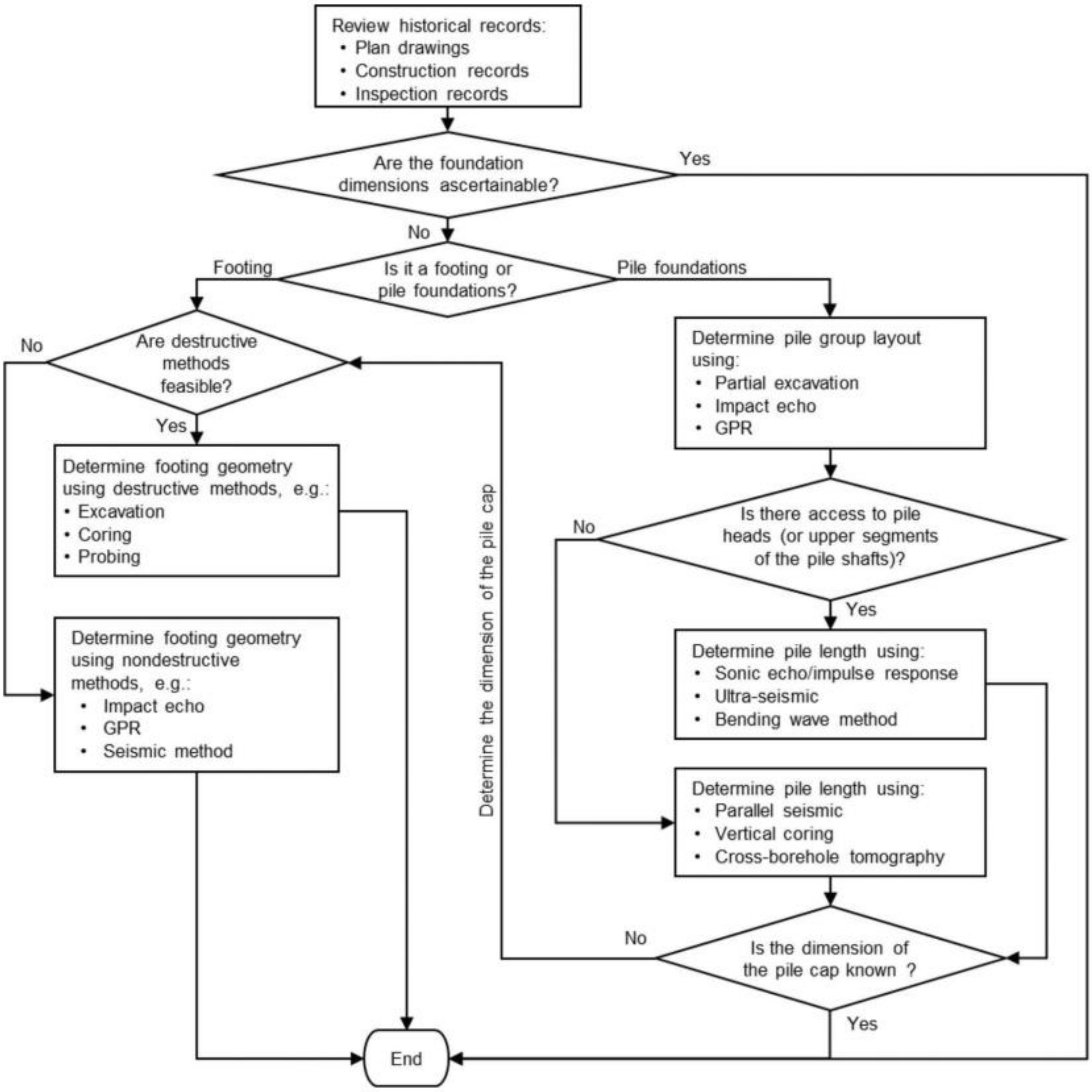

Figure 45. Flowchart to determine the geometry of the unknown foundation. (Lim et al., 2023, p. 34)

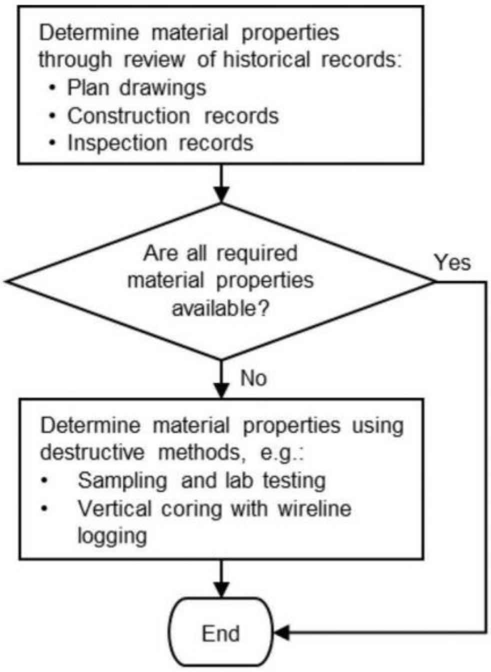

Figure 46. Flowchart for assessment of material properties of the foundation elements. (Lim et al., 2023, p. 36)

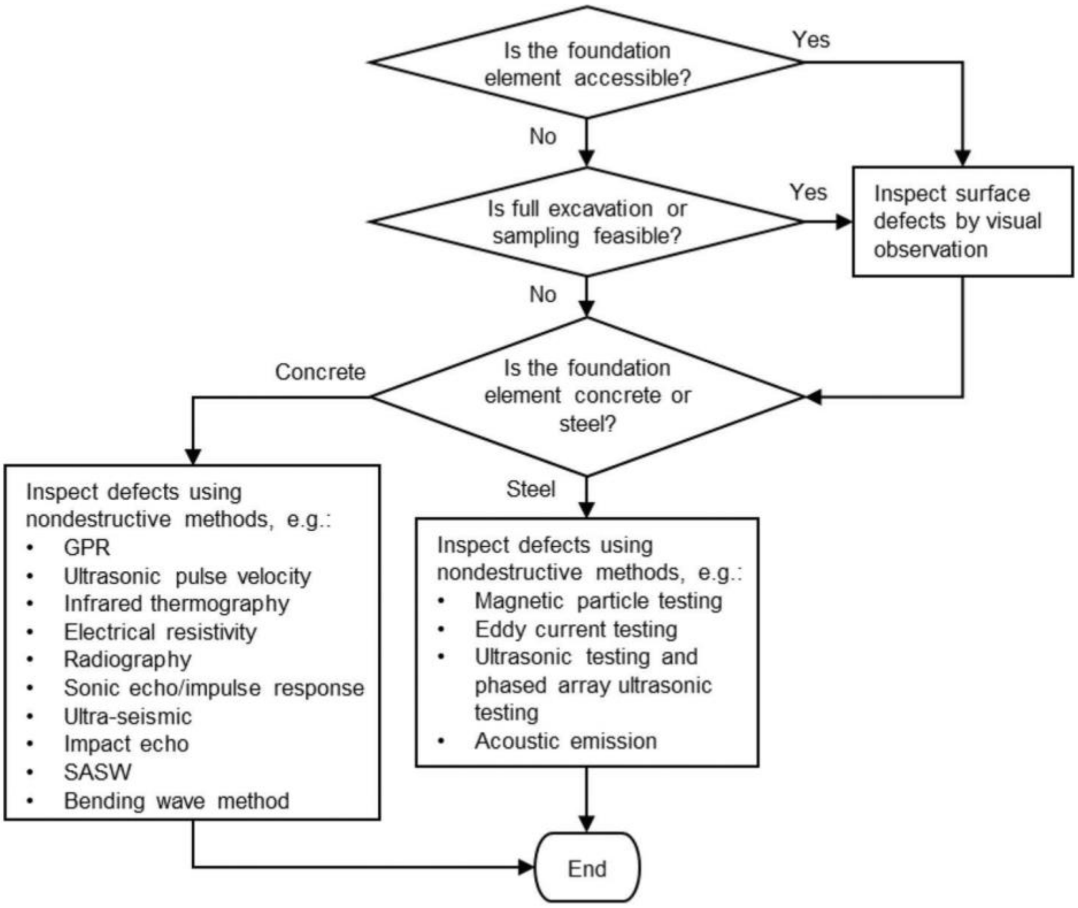

Figure 47. Flowchart for assessment of defects in existing foundation. (Lim et al., 2023, p. 36)

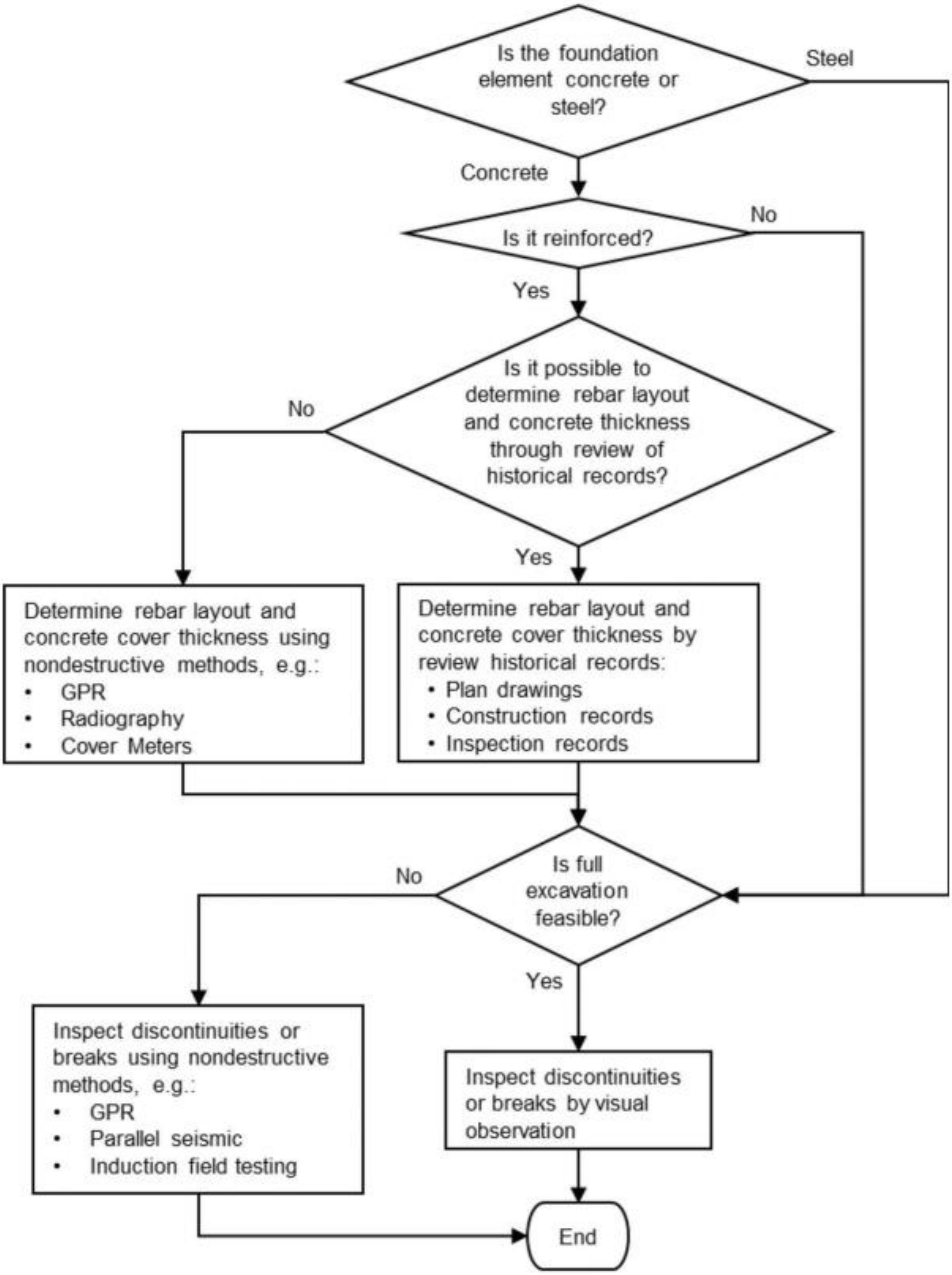

Figure 48. Flowchart for assessment of changes in geometry. (Lim et al., 2023, p. 37)

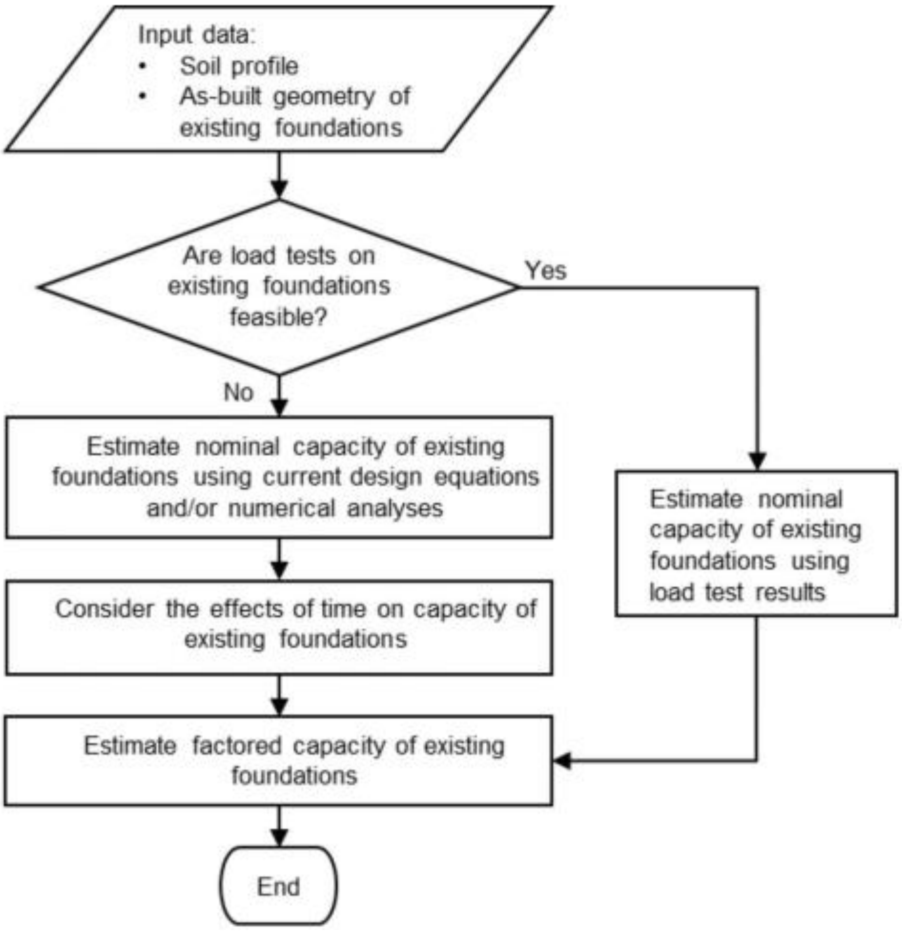

Figure 49. Flowchart to estimate the capacity of existing foundations. (Lim et al., 2023, p. 45)

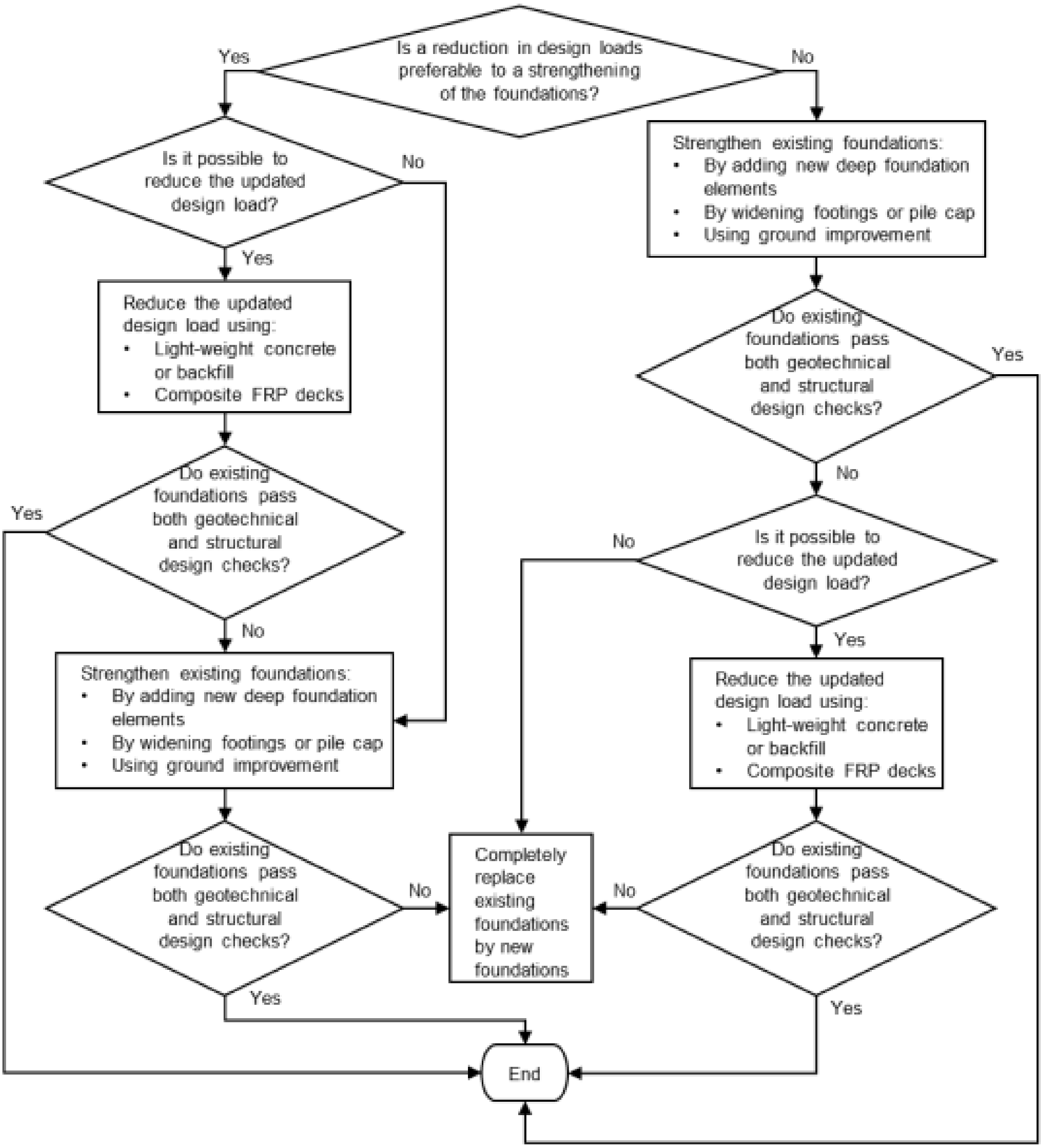

Figure 50. Flowchart to select foundation reuse solutions. (Lim et al., 2023, p. 62)

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