Master thesis

Master program in Energy Smart Innovation in the Built Environment, 120 credits

Transforming a Building by Implementing Circular Economy Principles

Thesis in Construction Engineering with Specialization in Renewable Energy, 30 credits

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Abstract

The thesis examines the influence of circular economy principles on the standard energy retrofitting practices of a residential building. It highlights the need for deep renovation actions in our building stock to achieve energy and carbonisation reduction. However, this need is usually satisfied only by applying business-as-usual deep renovation practices, which often justify using virgin materials to achieve energy reductions and neglect embodied carbon emissions from applied materials.

Therefore, it was necessary to show how the circular economy principles in building refurbishment practices can influence the reduction of carbon emissions and shift our focus from the present to future actions. A case study was chosen for demonstrating this potential through various qualitative methods, such as circular design approaches and reviewing material flows of applied materials while understanding their current and future life cycles. These methods led to tangible results, with reduced operational and embodied emissions. For example, operational carbon emissions were reduced by 38% when comparing the case study with the renovation of the existing building. The study also showed a common oversight - the influence of embodied carbon emissions from applied materials, which reduced overall carbon emissions in the case study to the existing building by 5%.

Further, this study presents a clear argument for an immediate shift from solely using virgin materials in building refurbishment. The high embodied carbon emissions from the initial production and construction of virgin materials, often applied in deep renovation, can counter the lowering of operational carbon emissions from the use phase of the building. The construction industry needs to transition from a linear to a circular economy, embracing reused and recycled materials to mitigate these emissions.

Keywords: circular economy, circular design approaches, energy retrofitting, embodied and operational carbon emissions, material flow, multi-lifecycle material

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Abbreviations

A_{temp}	Heated floor area
BAU	Business as usual
BBR	Boverket Building Regulations
CAV	Constant Air Volume
CE	Circular economy
CE LD	Circular Economy Linear degressive (approach)
CD	Circular design
CO_2	Carbon Dioxide
COP	Conference of the Parties
DfD	Design for Disassembly
DH	District heating
DHW	Domestic hot water
EC	European Commission
EC EF	European Commission Environmental Footprint
EOL	The end-of life (stage)
EPD	Environmental Product Declaration
EPS	Expanded Polystyrene
EU	European Union
FTX System	Exhaust and supply air ventilation with heat recovery
GHG	Greenhouse gas (emissions)
GWP	Global warming potential
HR	Heat recovery
HVAC	Heating Ventilation and Air-Conditioning system
LD	Linear degressive (approach)
MFA	Material Flow Analysis
RSP	Reference Study Period
SFP	Specific fan power
SGBC	Swedish Green Building Council
UN	United Nations
UNFCCC	United Nations Framework Convention of Climate Change
kgCO_2e	kilogram of Carbon Dioxide equivalent
kWh	kilowatt hour

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1. Introduction

The greenest building has already been built (Elefante 2007). The existing building stock in Europe is changing very slowly and, it is old, with more than 220 million building units, representing 85% of the EU´s building stock, built before 2001, and most of those buildings will still stand in 2050. Most of those existing buildings are not energy efficient. Many rely on fossil fuels for heating and cooling and use old technologies and wasteful appliances (European Commission 2020). Moreover, the building sector is responsible for 39% of global carbon emissions and large shares of global material use, including 50% of concrete and brick and 40% of steel. With an expected 60% growth of the urban built environment by 2050 and significant demand for housing upgrades in urban areas, decarbonisation of the building stock is critical to meet climate change mitigation goals set in the Paris Agreement (Nußholz et al. 2023). This situation is very similar to Sweden's.

In many places in Sweden, there are large residential areas that were built in the 1960s and 1970s. These were multi-family buildings for the period known as the Million-Homes Programme in the Swedish construction industry, and they account for roughly 20% of the existing building stock. These buildings are older than 50 years and need extensive renovations, such as replacing plumbing, ventilation, windows, and roofs (Olsson et al. 2015). Furthermore, this building stock was constructed when energy efficiency standards were not required, intensifying the need for refurbishments. The need to refurbish existing buildings is usually considered to be just a reduction in operational carbon emissions related to the use and maintenance of buildings. However, these actions neglect embodied emissions associated with constructing structures, representing between 31% and 44% of the total emissions for buildings with a 60-year expectancy. With the aim of the EU to lower greenhouse gas emissions (GHG) by 80-95% by 2050, compared to the 1990s levels, a significant reduction in embodied emissions in the EU construction sector will be required. This will need to go beyond improvements in production efficiency and negative emissions technologies and instead focus on lowering the use of high-impact construction materials (Gallego-Schmid et al. 2020).

One possible way to obtain these goals is a transition from a linear economy to a circular economy (CE), which could support minimizing resource depletion, environmental impacts, and waste within the built environment (Stijn 2023).

1.1. Background

According to Gallego-Schmid et al. (2020) and Stijn (2023), the current way of producing goods and services, which involves extracting natural resources, using them to make products, and then disposing of them after use, cannot continue indefinitely. Instead, we need to shift towards a CE that prioritises reusing biological and technological resources for as long as possible. This approach minimises resource input, waste, emissions, and energy leakage by slowing, closing, and narrowing loops. Narrowing loops means reducing resource use and achieving resource efficiency. Slowing loops refers to extending the lifespan of buildings, components, parts, or materials. Finally, closing loops means recycling materials from end-of-life products back into production. This shift is necessary due to the growing demand for resources and the environmental damage caused by their extraction and processing. For example, by 2050, annual global primary material extraction is set to triple, with 90% of biodiversity loss caused by resource extraction and processing.

The rising need for adopting CE principles, especially in sectors that use most virgin materials and raw products, such as the construction industry, has reached policymakers. One of these game-changing documents is the European Green Deal from 2019. In response to these challenges, it aims to promote a new growth strategy based on a resource-efficient and competitive economy with no net emissions from greenhouse gases by 2050. Another policy directive for the European Commission that has arisen from the European Green Deal is the Renovation Wave, which is based on the idea of addressing opportunities for energy efficiency and affordability in the existing building stock (European Commission, 2019, 2020b).

Although many buildings urgently need renovation, only 11% of the EU's existing building stock undergoes some level of renovation each year, and renovation works rarely address building energy performance. Energy renovations are approximately as low as 1% annually, and deep renovations that can cut operational carbon emissions by more than 60% are carried out in only 0.2% of the building stock per year (European Commission 2020).

Addressing the gap in understanding operational and embodied carbon emissions requires constant efforts from policymakers, industry, and society. Accelerating building renovation while prioritizing energy efficiency can achieve significant environmental, social, and economic benefits and, at the same time, prolong the lifecycles of the existing building stock.

1.2. Objectives

The main aim of the Master thesis is to explore the influence of circular economy principles on energy retrofitting in a specific case study. Furthermore, the purpose of the master thesis is to develop a model for a particular renovation scenario in cooperation with the company Familjebostäder. The developed model will be used to evaluate the impact of renovation actions on the case study object and assess the efficiency of implementing circular economy principles in such scenarios, possibly lowering carbon emissions by more than 50%. This will involve gathering empirics for the assessment of data such as material flow, energy consumption, improvements in energy efficiency and greenhouse gas emissions.

The objectives of the thesis are:

- Review the current material flow of materials and their short, medium, and long loops. Then, reuse processes in the construction industry, especially in residential buildings, as well as understand stakeholders' choices regarding circular building components.
- To analyse standard energy efficiency measures in building retrofitting and how those measures can be adapted to change during the building's lifecycle.
- To compare common building renovation strategies and assess how those strategies can implement circular economy principles through appropriate design approaches.

1.3. Delimitations

Despite the study's wide-ranging planning, covering all the necessary aspects within the given time frame is impossible. Factors such as social and economic sustainability and economic calculations were not included in the results and solutions of the study.

2. Literature overview

Building renovation is receiving increased attention in countries worldwide due to the ageing building stock and the need for more environmentally sustainable buildings with reductions in energy consumption and GHG emissions to limit their harmful climate impact. Many studies have claimed that increasing the energy efficiency of new and existing buildings is the solution towards creating a more sustainable building stock. However, it cannot be the only parameter used to define the robustness of a particular design solution, especially in building refurbishment practises. It is the first important step to accomplish sustainability. Many studies focus on inventing and designing new technical solutions and developing new methods to calculate, simulate, and dimension the physical and technical aspects of renovated buildings, these approaches alone are insufficient to make building renovation more sustainable. Therefore, it is essential to have a holistic approach encompassing social, economic, and environmental aspects, which can be referred to as environmental efficiency (Brambilla et al. 2018; Jensen et al. 2018).

To achieve environmental efficiency in the existing building stock, it is necessary to focus on lowering both operational and embodied carbon emissions of the building or carbon emissions that arise throughout the whole life cycle of the building. Operational carbon emissions are related to the environmental impacts of buildings from heating, cooling, and lighting and can lead to both a proportional and actual increase in embodied impacts. On the other hand, embodied carbon emissions are impacts from individual materials and components. These components arise throughout the whole life of the building. This includes emissions from materials and components' manufacture, transport, and construction activities. It also includes emissions from the refurbishment and replacement during the use stage of the building's life cycle. Additionally, it includes emissions from the demolition and waste processing of these materials and components during the end-of life (EOL) stage of the building's life cycle. Because of its impact, reducing embodied carbon emissions has increasingly been recognized as a crucial focus area for enabling effective climate mitigation in the building industry, and one way to reduce operational and embodied carbon emissions in the existing building stock is through applying CE strategies (Moncaster et al. 2019; Nußholz et al. 2023).

The concept of adopting CE strategies and promoting circular buildings, can be considered as complementing without overlapping the definition of sustainable building (González et al. 2021). Additionally, several studies have been conducted for implementing CE strategies in the existing buildings stock:

- Çetin et al. (2021) analysed different barriers and enablers during the implementation of CE principles in the social housing stock in the Netherlands.
- Stijn (2023) has created a comprehensive approach towards circular building components by analysing existing CE frameworks and design approaches to the extensive application of Life Cycle Analysis (LCA) and merging with CE strategies.
- Nußholz et al. (2023) analysed CE strategies in 65 different examples in literature and practice and how those strategies have been applied to new, renovation, and demolition projects.
- Fernandes & Ferrão (2023a) have created a new CE framework, which can be applied to building refurbishment projects based on existing frameworks.

The literature overview focuses on analysing the implementation of CE strategies in building refurbishment practises, focusing on achieving environmental efficiency while reducing operational and embodied carbon emissions. Moreover, the overview will analyse various CE strategies proposed in the literature, such as narrowing, slowing, and closing resource loops in building refurbishment projects. It will also examine barriers and enablers in the construction industry regarding the adoption of CE strategies. Then, it will explore existing frameworks and methodologies developed to integrate CE principles into building refurbishment projects, including allocation approaches and their ability to merge with Life Cycle Analysis (LCA). The literature overview will draw upon academic studies to understand the current knowledge regarding integrating CE principles in building refurbishment practises.

2.1. Policies and frameworks for building renovation and circular economy adaptation

Over the past decades, numerous policies and frameworks have been established, with the goal of reducing energy consumption in buildings and lowering carbon emissions generated during building construction and the operational phase.

The initial move was taken globally through the United Nations Framework Convention on Climate Change, the UN body. This body is dedicated to facilitating the worldwide response to climate change. One of the significant contributions of this body are the Conference of the Parties, or COP, in 2015, when the Paris Agreement was adopted. It sets long-term goals to guide all countries to reduce global greenhouse gas emissions to hold global temperature increase below 2°C above pre-industrial levels and pursue efforts to limit it to 1.5°C pre-industrial levels (UNFCCC 2016).

On the other hand, at the European level, many different policies and frameworks have been developed from this agreement, especially in the field of built environment. The building stock is a high priority for improved energy efficiency in the EU. Central objectives in the EU for 2030 are to improve overall energy efficiency by 32.5% and to reduce GHG emissions by 55%, compared to 1990 levels. For example, directive EU/2018/44 on the energy performance of buildings guides members states in how to achieve these goals through deep energy retrofitting of the existing building stock, primarily focusing on worst-performing buildings, and a near zero-energy standard for new construction (von Platten et al. 2021).

According to (Gustavsson & Piccardo 2022), energy efficiency standards for buildings are cost-effective instruments to reduce GHG, contributing to the lower total energy demand of buildings. Energy efficiency standards apply to both new buildings and existing buildings undergoing major renovations. Existing buildings represent a significant energy-saving potential, especially in those countries having an established building stock. Energy retrofits can improve the thermal performance of the building envelope, as well as the energy efficiency of technical installations for heating and cooling, at different performance levels. High energy performance retrofits, namely deep energy retrofits, can reduce the heat energy demand by well over 50% in existing buildings and thus help achieve the European target of 55% GHG emissions reduction by 2030.

Therefore, the European Commission created several policies and frameworks to address the overall need for better-performing existing buildings while maintaining embodied and operational carbon emissions at the aimed level. One is the European Green Deal (European Commission, 2019), which aims to reduce carbon emissions from industries depending on virgin materials, such as the construction industry. Another one is the Renovation Wave (European Commission, 2020b), a strategy born from this initiative. The Renovation Wave strategy has focused on developing and promoting steps for member countries to focus on deep renovations in their building stock. Although this strategy aims to help member countries achieve ambitious targets for building renovation, especially for the years 2030 and 2050, it also focuses on promoting steps to create a holistic approach to address aspects beyond energy efficiency. This holistic approach includes improving the affordability of housing stock, integrating renewable energy sources, and implementing life cycle thinking and circularity in the built environment. The holistic approach is essential for deeper renovations to reduce the use of virgin materials and their embodied emissions. One way to reduce the use of virgin materials and to minimise existing and future embodied carbon emissions is the action plan proposed by the European Commission (European Commission, 2020a). Based on

circular economy principles, it will guide the transition in all resource-intensive sectors, such as textiles, construction, electronics, and plastics (European Commission, 2019, 2020a, 2020b).
This action plan by the European Commission (2020a) aims to promote circularity principles throughout the life cycle of buildings by:

1. Addressing the sustainability performance of construction products and introducing recycled content requirements for construction products.
2. Promoting measures to improve the durability and adaptability of built assets in line with the CE principles for building design.
3. Integrating life cycle assessment into public procurement, as well as exploring the appropriateness of setting carbon reduction targets.
4. Considering a revision of material recovery targets as part of the EU´s legislation.
5. Promoting initiatives to reduces soil sealing, rehabilitate abandoned or contaminated brownfields.

Although it is encouraging that many laws, strategies, and plans have been adopted at different legislative levels to achieve the carbon emissions goals of 2030 and 2050, many things still need to be improved, especially at the national level.

2.1.1. Sweden

According to von Platten et al. (2021), Sweden tends to have more ambitious energy and climate policies than the EU in general, and apart from complying with EU regulations, Sweden has a national target to reduce energy intensity to GDP by 50% from 2005 to 2030. Moreover, Sweden has also implemented the Climate Act, a national implementation of the Paris Agreement, by which Sweden aims to have zero GHG emissions by 2045. By implementing this act, Swedish government´s climate policy must be based on climate goals, present climate reports, and action plans to achieve the desired climate goals of lowering GHG from activities and all industry sectors by 85% in 1990s level by 2045 and after 2045, aiming towards negative emissions (Ministry of Climate and Enterprise 2021).

Since the launch of the Circular Economy Stakeholder Platform by the European Commission, national, regional, and local authorities have used the platform to share their strategies and roadmaps. Sweden also followed that way and adopted the Swedish circular economy strategy, known as the “Circular Economy-Strategy for the transition in Sweden”, in 2020, with the idea of transitioning to a circular economy and following the Sustainable Development Goals in the 2030 Agenda. Although Sweden, as a country, has adopted different strategies regarding the implementation of a circular economy, the idea of it is still not widely spread because the circular or secondary use of the material in Sweden was 7.1% in 2016 and 2019, which compared to the EU average of 12.8%, leave much space for improvement (European Commission 2022).

Different strategies and action plans are being adopted in European countries to implement CE principles to reduce operational and embodied emissions in resource-dependent industries, such as construction. Sweden has taken a step in the same direction by introducing national legislation to lower operational carbon emissions from existing buildings. The national legislation related to the renovation of the existing building stock is known as the Third strategy for energy-efficient renovation, and it is a part of Sweden´s integrated national and climate plan complied with European Parliament and Council regulations. This strategy represents a further development of two previous strategies, which are based on extensive research for national legislative bodies, such as the Swedish National Board of Housing, Building and Planning (Boverket) and the Swedish Energy Agency (Energimyndigheten).

Decarbonisation of the Swedish housing stock has progressed successfully since the oil crisis in the 1970s, and the housing stock is today highly decarbonised with district heating dominating in multifamily buildings. Consequently, having come far on the journey towards decarbonisation, much attention is now being directed towards improved energy performance in the housing stock in general, and in the multifamily housing stock in particular (von Platten et al 2021). Apartment buildings account for 51% of all residential buildings in Sweden, and 61% of apartments in apartment buildings were built from 1941 to 1980. It is assumed that most of these buildings will be renovated in different periods up to the year 2050, with various renovation scenarios from light to deep renovation. Besides various scenarios, the national legislation proposed milestones to be accomplished by 2050 in the built environment. The milestones indicate the expected changes in energy consumption per building type over a decade compared to previous periods. Moreover, these milestones are consistent with Swedish energy and climate policy and contribute to the achievement of the European Union´s goal of improving energy efficiency (Boverket & Energimyndigheten).

2.1.2. Gothenburg

Much like the national level, the city of Gothenburg has taken steps to reduce operational and embodied carbon emissions in various industries. To this end, the city adopted its own environmental and climate programme to create a common platform for strategic environmental work to lower net carbon emissions from all sectors between 2021 and 2030. The programme focuses on the biggest challenges for an ecologically sustainable city and contains three environmental goals: nature, climate, and people, and each category has sub-categories.

As part of the strategic climate goal, a sub-category is dedicated to reducing energy use in residential and non-residential buildings. The aim is to use energy more efficiently so that it is possible to create an energy system that uses renewable energy sources without having a negative environmental and climate impact. Hence, the primary energy use needs to be reduced by at least 30% for inhabitants by 2030 compared to 2010. In the case of residential buildings, this means a reduction from 120 $^{kWh}/_{m^2}$ in 2010 to 84 $^{kWh}/_{m^2}$ in 2030 (Göteborgs Stads Miljö-Och Klimatprogram 2021-2030 2021).

On the other hand, the city of Gothenburg has not yet implemented legislation for a circular economy. However, the city of Gothenburg has led a research project, Future Scenario 2030: Circular Procurement of Construction and Demolition projects (Gerhardsson et al., 2019), collaborating with multiple actors to create a plan for adopting circular economy principles in the construction industry. The plan focuses on preserving existing buildings with limited refurbishment actions, while new buildings will use more recycled and reused materials and fewer virgin or raw materials. The plan proposes different procurement methods for building refurbishment projects based on material resource management, material longevity, and possible life cycles. The plan also advocates for the adoption of sustainability effects of material resource management, which includes not only environmental but also social aspects and the climate declaration of used materials - whether recycled or virgin. Although climate declarations are part of national legislation for new buildings and will soon be required for refurbishment buildings, the plan proposes standardizing future climate declarations from a life cycle perspective of materials. However, such declarations might not reflect the overall sustainability of chosen materials. By adopting a broader climate declaration method, measuring the economic, social, and environmental consequences of used materials will be possible (Gerhardsson et al. 2019).

2.2. Circular Economy in the Built Environment

This section discusses CE strategies' definitions and principles and how they can be applied in building refurbishment practises. Additionally, it identifies the key challenges when adopting CE strategies in the existing building stock.

2.2.1. Definitions and principles of Circular Economy in the Built Environment

According to Castro & Pasanen (2019) and Van Stijn & Gruis (2019) The building sector consumes 40% of natural resources globally, produces 40% of global waste and 33% of emissions, and is one of the largest contributors to GHG in the world. With estimated population growth and its resulting urbanization, it is reasonable to foresee the growing demand of resources by the building industry. If this demand is met solely by further material extraction, it will lead to further environmental degradation. Therefore, the transition to a CE, where materials are kept inside the production loop to reduce further material extraction, is very important.

The CE, according to Castro & Pasanen (2019) and Van Stijn & Gruis (2019), can be summarised in the following three principles:

1. Preserving and enhancing natural capital by controlling finite stocks and balancing renewable resource flows.
2. Optimising resource yields by circulating products, components, and materials at their highest utility and value always in both technical and biological loops.
3. Fostering system efficiency by revealing and designing out negative externalities. Due to its high impacts, the transition to a circular built environment is pivotal to achieve a resource ‘effective’ and sustainable society.

However, even though this change is necessary, certain things regarding implementing CE strategies in the built environment remain unknown. Buildings still have not been seen as identifiable systems, especially regarding how to influence changes to their delivery within a complex system. Other issues include the suitability of circular business models when applied to construction's inherently longer periods, the possible benefit of building materials held as stock, the impact of changing ownership over time, or current ambitions and guidance on sustainable development and the differences (Campbell 2018).

Although there are still lingering questions regarding implementing CE strategies in the built environment, applying them in the built environment implies multiple approaches closely related to sustainability. For instance, both sustainable construction and the principles of the CE are long life, high recycled content, adaptability and flexibility, and intent to use renewable materials. Nevertheless, specific approaches are different. For example, the 3R´s principle, Reduce, Reuse, and Recycle, is a well-established action plan in the construction sector as a sustainability strategy to lower harmful environmental impacts and design out waste. However, the 3R’s was appraised as insufficient for a CE transition, and hence expanded to the “R-List” which includes additional actions arranged by a priority order as follows: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover. However, perhaps more apparent within the circular economy principles than sustainable construction is that these aspects rely on new and viable markets for a circular model to work. Remaking or sharing strategies are opportunities for new business and challenges in breaking down embedded methods and attitudes (Campbell 2018; Rahla et al. 2019).

It is necessary to distinguish CE implementation levels in the built environment to achieve that transition and move from an established way of thinking. As a result, CE strategies can be applied at either a city level or macro level, mezzo level or building scale and finally, micro level or product scale. Furthermore, for the transition to a CE to be successful, it is also essential to understand the economic, environmental, technological, social, government and behavioural dimensions (Campbell 2018; Kanters 2020).

Besides the importance of comprehending different scales of CE strategies scope and various dimensions to transition from a linear built environment to a CE built environment, a focused framework for existing buildings is much needed, mainly because the existing building stock is an integral part of the built environment which can be used more circular through retrofitting. Additionally, when considering building retrofits with the additional lens of embodied carbon emissions, it becomes evident that retrofitting existing buildings rather than tearing them down and replacing them with highly efficient new buildings will almost always provide the best overall climate value. The need for retrofit moments can also be further developed to make the stock circular at all levels: the housing stock, dwelling, components, parts, and materials (Clark et al. 2023.; Kyrö 2020; Van Stijn & Gruis 2019).

2.2.2. Circular Economy Loops

The concept of CE has been embraced as a strategy to minimise resource inputs and outputs by introducing cycle principles, avoiding waste and pollution, and creating regenerative systems. Since it was introduced, it has gained the attention of policymakers, who created several strategies and action plans in which the built environment plays a pivotal role. Therefore, it can be said that the CE paradigm, especially in the concept of the built environment, has originated from several theoretical backgrounds, such as Industrial Ecology and Biomimicry. CE paradigm can be interpreted in the built environment as a set of strategies to maintain resources at their highest possible quality for as long as possible while using renewable energy and environmentally low-impact, toxic-free materials. Moreover, as already mentioned, CE is “a regenerative system in which resource waste is minimised by slowing, closing and narrowing material and energy loops”.

In this case, it can be concluded that loops influence the shape of CE. For example, in recycling theory, closed loops refer to recycling for the same quality or use. In contrast, in circular supply chains, closed loops refer to various value retention processes realised by the industry partners involved in the original production. A closed-loop approach makes it easier to control the flow of resources to ensure they are cycled at the highest utility and value. This gives suppliers and manufacturers a clear incentive to develop designs that can be easily repaired, reused, refurbished, and recycled. On the other hand, in an open loop CE, resources cycle from user to user through platforms and companies which offer make, use and re-make services. The open loop CE can ensure continuing access to resources and the means of production. However, fragmentation of stakeholders might make resource flows harder to control, inhibiting the cycling of resources at their highest utility and value (Çetin et al. 2021; Nußholz et al. 2023; Stijn 2023). However, these strategies, based on CE loops, are further developed for the built environment, and summarised under four categories of principles that Çetin et al. (2021), Nußholz et al. (2023) and Stijn (2023) suggest:

1. Narrowing resource loops or using fewer resources per product.
2. Slowing resource loops or keeping the product in use as long as possible.
3. Closing resource loops or recycling materials.
4. Regenerating resource loops or using renewable resources and regenerating the natural environment.

Nevertheless, not all strategies are equally represented, especially in building refurbishment cases. In an extensive study by Nußholz et al. (2023) a combination of narrowing, slowing and regeneration of resource loops was found in renovation projects, showing a great potential for combining strategies. These strategies have a great potential to improve efficiency for the use of buildings and enable materials reuse and choice of materials with lower carbon impacts. However, cases enabling the reuse of materials and components of the existing building were only found amongst the cases sourced from the grey literature, indicating a research gap in academic literature.

Another study, by Van Stijn & Gruis (2019) agrees with the findings mentioned earlier, and proposes a circular retrofit strategy, especially for buildings with fragmented mixed ownership. The strategy involves retrofitting the existing housing stock with modular, mass-customizable, and "cyclable" products. This solution can facilitate a component-by-component retrofit that is designed using circular design strategies and principles. The goal is to integrally narrow, slow, and close the loops on the building, building component, part, and material level. This approach ensures that the design of components can be used along and beyond their life cycle. Additionally, the absence of relevant circular economy frameworks tailored for building refurbishment cases magnifies the situation, particularly in residential buildings, where adaptability tools and frameworks are predominantly geared towards commercial and office buildings, which are easier and usually less costly to adapt (Ollár 2024).

2.2.3. Conceptual Framework for CE in the building refurbishment practice

Given the limitations of green and sustainable buildings, which mainly focus on the design and use of life-stages of buildings and merely on their EOL scenarios, circular buildings have arisen and been put forth as a more holistic approach to CE in the built environment. Academia and non-governmental institutions promoted the reliability and efficiency of circular buildings to ensure a better transition towards CE. Still, research and scientific contributions to circular buildings barely scratch the surface regarding producing buildings that match Sustainable Development Goals (United Nations, 2022).

Moreover, two CE frameworks are the most used today. The first framework, by the Luebkeman & Fellow (2016), known as the RESOLVE framework, is based on regenerating, sharing, optimising, looping, virtualising, and exchanging ideas. The second one is defined on the premise that a building is designed, planned, built, operated, maintained, and deconstructed in a manner consistent with CE principles by Kyrö (2020), Pomponi & Moncaster (2017) and Rahla et al. (2019). Although implementing CE principles can be challenging, especially in refurbishing existing buildings, several frameworks and methodologies are available to help simplify the process. Many of these frameworks are based on existing CE frameworks for the entire building environment adapted for the building level and are further explained in the literature overview.

The first framework is from the study by Kyrö (2020), which conducted an extensive systematic literature review to examine the gap in the CE framework for existing buildings. This systematic literature review started with a scope of 144 related to the theme of CE in the built environment. It was narrowed to 14 articles, which covered the implementation of CE principles to the existing building stock at the mezzo or building level. Further, this study distinguished found approaches in articles based on the above RESOLVE framework. The most identified features from the literature relate to closing the material loops and designing for the future. However, these approaches are primarily relevant for new construction, not existing buildings. The approaches identified as most relevant for existing buildings comprise according to Kyrö (2020):

1. The share approach involves sharing with it both technological and cultural prerequisites and a paradigm shift from ownership to access.
2. The optimised approach emphasises the importance of optimising the useful life of buildings, and it is divided into Preserving and Adapting categories, in which the first category relates to the ongoing maintenance of buildings, while the second is related to more intrusive changes to maintain functionality and optimise use.
3. The virtualization approach emerges in sharing by using online solutions present in the sharing economy.
4. The exchange approach, named Rethink, expands the idea, and better reflects the general CE principles. It comprises all novel circular business models that challenge the existing ownership paradigm and new production.

On the other hand, the second framework is from the study by González et al. (2021), who researched the gap in existing CE frameworks, especially those related to measuring overall circularity at the building level, and therefore created a framework for holistic Circularity measurement and assessments based on the compliance of the CE principles. Moreover, this CE assessment methodology, includes the definition of the key parameters and evaluation criteria to characterize if a building or a major refurbishment is circular. This approach focuses on the evaluation from an impact assessment and circular flow perspective together with the business perspective evaluation so it can guarantee economically viable business models that can support the mid-and long-term economic activity of retrofitting under the CE principles. So, critical steps in this framework are as follows according to González et al. (2021):

1. The process to monitor and the identification of the processes to monitor material inputs.
2. Design.
3. Production and delivery.
4. Consumption or EOL resource management.

For the building and construction sector, the critical processes are in all the four life cycle stages according to González et al. (2021):

1. At the product stage these critical steps are the material inputs and manufacturing processes of all building parts and components.
2. At the construction stage they are the supply chain and the building construction or refurbishment activity itself, and how different products in a building are interconnected to ensure future disassembly.

3. At the use stage there is energy consumption, maintenance operations, as well as the rotation of materials during building´s use phase.
4. At the end of use stage, the resource and waste management activities are the most relevant processes.

Like the first mentioned study, this methodological framework addresses the six principles of CE applicable to the built environment under the framework by Luebkeman & Fellow (2016), also at the mezzo or building level (González et al., 2021).

Finally, the third framework, also focused on the building level, is from the study by Fernandes & Ferrão (2023). The methodology for creating the Circular Refurbishment Framework is based on the three pillars of CE: waste reduction, resource reduction, and product utility enhancement. It combines three existing concepts: the 9R framework, the LCA approach and the Procurement Phases. Moreover, the 9R framework prioritizes waste avoidance, and the first steps correspond to the pre-use phase, including refuse, rethink, and reduce strategies, while extending the lifetime of products includes reuse, repair, refurbish, remanufacture, and repurpose strategies. The post-use phase includes recycling and recovering. When applied to building refurbishment, the EOL of the building is considered when it no longer serves its inhabitants' needs and requires refurbishment. The other steps of the 9R framework can be applied to building components. The LCA approach consists of four stages: product stage, construction process, use stage, and EOL. It also considers the reuse, recovery, and recycling potential. When considering a CE refurbishment context, mapping the existing building condition is usually the first stage in refurbishment strategies for existing buildings. It is also considered when deciding on refurbishment options using the LCA methodology. After mapping, setting refurbishment options that align with CE is essential to prevent waste and optimize resources. The procurement phases are like a cradle-to-gate system boundary and include strategic definition, preparation and briefing, concept design, spatial coordination, technical design, manufacturing and construction, handover, and use. The new framework comprises six stages to facilitate CE adoption in building refurbishment that Fernandes & Ferrão (2023a) suggest:

1. The first stage is mapping and is dedicated to characterising the existing building.
2. The second stage is selective disassembly and demolition.
3. The third stage consists of the conceptual and detailed designs for construction or the (re)design stage.
4. The fourth stage comprises the new products that will be used.
5. The fifth stage is the construction stage.

6. The sixth stage is the operation, which is related to the use of the building.

The given frameworks provide insight into current research regarding the adoption of CE principles in building refurbishment practises. All the given frameworks represent the research gap in existing frameworks and are based on the extensive research in existing literature. Although the analysed frameworks share similarities, there are some notable differences among them. For example, each framework addresses gaps in existing frameworks in the implementation of CE principles, however, they all use different methodologies, and have variations in measurements and assessments, while others highlighting different key principles. Moreover, some of these frameworks cover the overall holistic approach to existing building stock, other focus on addressing the existing CE material loops.

2.2.4. Assessing Circularity in Existing Buildings: Challenges for Adopting Circular Economy Principles

Besides the lack of a comprehensive, holistic approach towards adopting CE strategies in the existing building stock, measuring the building´s circularity according to the mentioned CE paradigm at the building level is also necessary. However, measuring progress towards a CE practice is challenging; a set of indicators is required to seize the main factors of CE in buildings, such as the lifecycle of involved materials, input/outputs of different aspects and the building´s end-of-life scheme. Measuring circularity of existing buildings is necessary to effectively monitor the material salvaging potential in the renovation projects. Furthermore, system thinking is crucial for refurbishment projects, as designing out waste and closing the loops needs holistic thinking regarding renovation measures (Almeida et al. 2023; Rahla et al. 2019).

As mentioned, the definition of CE, particularly in the context of the built environment, is still unclear. There is no common consensus among different stakeholders in the construction industry on what implementation of CE strategies requires. This leads to various interpretations of these strategies and challenges to implement and monitor them in the built environment. Moreover, this is especially evident in the case of existing buildings. Compared to measuring sustainability and improving the energy efficiency of existing buildings, which is a relatively straightforward process, measuring existing building circularity is more complex. Usually, in the case of existing building stock, CE strategies focus on EOL treatment, which involves dealing with different building components and materials with varying life cycles and undefined service lives. As a result, it is challenging to establish a model for whole building reuse. Therefore, some experts suggest using sharing layers to distinguish each building component according to its lifespan.

According to Castro & Pasanen (2019), Frank Duffy argued that buildings are "…several layers of longevity of built components". This introduced the idea that building elements changed at different rates based on their function. Originally, Duffy included four layers: shell, services, scenery, and set. Later Brand expanded these into "six shearing layers of change" including the original four (renamed) structure, services, space planning, and stuff, adding site and skin. Each layer has an average service life based on material durability, technological life, and owner's preference. Figure 1 shows building´s shearing layers of change.

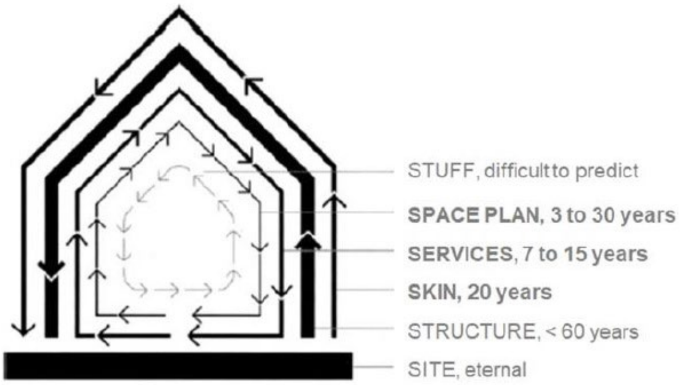


Figure 1. Building´s shearing layers of change (Source by Castro & Pasanen (2019).

This approach considers buildings' dynamic structures that can adapt and remain flexible in future scenarios, which is essential for achieving true CE principles.

One of the main obstacles to adopting CE strategies in building design is the lack of clear circularity indicators. These indicators should measure the impact of a building on the environment, economy, and society and guide the selection of components that enable CE strategies such as narrowing, slowing, and closing material loops. Additionally, they should objectively evaluate the building's development towards circularity. Another challenge is the lack of practical approaches to data collection, especially for existing buildings. While many programs can effectively collect and measure existing materials, knowing what is important to measure is still essential. Therefore, many authors suggest that measuring the materials in and outflows of building components while also considering components' lifespan and the possibility of overlapping lifespans should be mandatory when assessing the circularity of existing and future buildings. Finally, there is ambiguity in the weighting and scoring of buildings' circularities. For instance, ambiguity in scoring and weighting is one of the main issues encountered while assessing the environmental aspect of buildings. At the same time, the complexity of CE strategies, which cover several dimensions of building components with fluid indicators, cannot create a singular framework to cover all aspects of buildings' circularity (Rahla et al. 2019).

2.3. Energy Retrofitting and Renovation in Building Adaptation

This section aims to provide a deeper understanding of building adaptation, particularly how energy retrofitting and renovation of existing buildings can influence the overall sustainability and resilience of built environments and how those approaches comply with the case study. Housing renewal has been recently pursued to achieve more sustainable societies across Europe, including energy efficiency measures, accessibility, accommodating ageing populations, and improving social integration, especially in neighbourhoods with lower-income families (Femenías et al. 2018). Furthermore, this section will examine energy retrofitting strategies and standard renovation practises to give a closer look at these procedures and how they can further influence the steps needed to adopt the principles of CE in building retrofits. Additionally, the chapter will provide insights into both the barriers and enablers regarding energy retrofitting of buildings.

According to a recent study by Shahi et al. (2020), a building facing obsolescence is often economically unsustainable, provides low occupant comfort and satisfaction, and has increased energy use and water consumption. Therefore, having responsive, appropriate, and timely building adaptation and renewal is crucial to extending a building's effective lifespan. By doing so, it is possible to reduce the inflow of virgin materials, lower current and future carbon emissions, and enjoy social advantages while also having the economic advantage of lowering the expenses required for building new buildings. However, to understand the benefits and obstacles of building adaptation further, it is necessary to distinguish between different terminologies used in the literature for building adaptation projects. Therefore, according to Shahi et al. (2020), building adaptation projects can be divided into refurbishment and adaptive reuse. Subcategories of refurbishment include retrofitting, rehabilitation, and renovation, while adaptive reuse involves building conversion and material reuse.

In the case of building refurbishment, it can be seen as the process of improving the existing conditions of a building. It may include the addition of elements for the improvement of energy efficiency. However, it needs to be seen as a renewal and upgrading of the building standard to be closer to the current standard rather than the standard when the building was originally built, with an extending period of usually 50 years. It is also the umbrella term for retrofitting and renovation (Femenías et al. 2018; Jensen et al. 2018; Shahi et al. 2020).

As a part of building refurbishment, energy retrofitting of buildings is essential with the current state of the built environment. Most buildings constructed over 50 years ago will still exist in the future. However, these buildings are incompatible with contemporary energy efficiency and comfort standards. To solve this problem, deep renovation of existing buildings and high-energy performance retrofits can reduce the heat energy demand by more than 50% compared to pre-renovation levels. Energy retrofitting usually involves improving the building envelope, which includes walls, roofs, floors, and transparent elements. In addition to improving the building's envelope elements, it is also necessary to enhance HVAC efficiency and integrate renewable systems to reduce heat and cooling demands.(Femenías et al. 2018; Gustavsson & Piccardo 2022; Shahi et al. 2020).

On the other hand, building renovation has many definitions. However, it can be said that renovation is defined as the process of replacing or repairing outdated building components or remodelling the interior spatial layout of buildings to address issues such as lack of not only energy efficiency but even economic viability or occupant satisfaction while maintaining the building's function. Therefore, the primary goal of the renovation is to restore the building's original conditions and enhance its architectural aspects and appearance for improved comfort and attractiveness, as well as energy requirements but also the social and economic requirements of occupants (Shahi et al. 2020). Therefore, building refurbishment, both renovation and energy retrofitting, with their strategy, is necessary to decrease energy consumption and improve the quality of life for residents (Femenías et al. 2018).

However, acknowledging the complexity of sustainable building refurbishment with its categories, such as energy retrofitting and renovation, is essential. This process involves various social, cultural, and financial factors. Many experts agree that we need to address the motivation behind every building renovation (Femenías et al. 2018). Often, the purpose is not just to enhance energy efficiency and improve the comfort of the occupants. Instead, it is to address social issues and change the image of the neighbourhoods. Although, this approach can lead to gentrification, which needs to be considered. To better understand the decision-making process involved in all these factors, it is necessary to understand the standard steps required for building refurbishment, which is especially crucial when it comes to sustainable building adaptation, as it requires the implementation of circular economy principles.

Therefore, the required steps can be identified if the building is connected to the district heating system to accomplish building refurbishment. However, in both cases, the first steps involve adding insulation to the exterior and interior layers of the building with temperature differences and replacing existing windows with new ones. On the other hand, in the cases when buildings are not connected to existing district heating systems, it is necessary to, besides additional layers of insulation, integrate renewable energy sources, such as solar panels, wind generators, and biomass-fuelled cogeneration systems, which can satisfy building heat and cooling demands (Gustavsson & Piccardo 2022; Luo 2023). Another powerful tool for satisfying energy efficiency requirements and enhancing architectural aspects to improve comfort and attractiveness and satisfy social and economic requirements are additional elements of glazed areas or additional volumetric solutions. Balconies, winter gardens, and rooftop extensions add living spaces and new architectural value to the existing building (Femenías et al. 2018).

From the time perspective and planning steps needed for building refurbishment, according to (Shahi et al., 2020), building refurbishment projects can be divided into three categories to include minor, medium and major refurbishment works. Minor refurbishment considers the next five years and involves maintenance and repair objectives that are economically justified within this shorter time frame. Medium refurbishment considers the extension of the economic life of the building by 15 years and involves the improvement of building finishes and services and excludes structural repairs. Major refurbishment considers the life of the building beyond 15 years and involves significant alterations to an existing building, including structural, to make it comparable to a newly constructed building.

The study conducted by Mjörnell et al. (2019) was an extensive exploration of the various approaches taken by fourteen housing companies in Sweden, both private and public-owned, towards rental housing. The study focused on the companies' strategies for renovation, ranging from partial to deep renovations, with a commercial or societal focus. By analysing the data, researchers could identify common trends and conclude the most popular approaches to building adaptation. The study revealed that most public and private companies with a more robust social commitment prefer step-by-step renovations, allowing tenants to remain in their apartments while energy efficiency measures are implemented. These measures typically include replacing windows, installing heat recovery ventilation, controlling heating and ventilation systems, and implementing energy-efficient lighting. On the other hand, private companies driven by profit and property value are more likely to focus on deep renovations designed to meet higher energy efficiency standards.

Moreover, a recent study by (Femenías et al., 2018) explored a renovation strategy encompassing energy efficiency and renovation as part of building refurbishment. This study distinguished the renovation strategy between privately and publicly owned renting companies. Private companies prefer deep renovation, focusing on long-term financial goals when investing in energy efficiency. On the other hand, municipal housing companies prefer deep renovation strategies where they can demonstrate social and environmental responsibilities, typically in neighbourhoods with low-income tenants. The same study explains the reasons for step-by-step or partial renovation, which private and public companies' practice. Such renovations are often budget-limited or aimed at minimizing the disruption to current tenants, and energy efficiency may only sometimes be the primary goal or may be achieved over time.

It is essential to identify the main obstacles to sustainable building refurbishment, in addition to common strategies for refurbishment and practises, especially in privately and publicly owned companies. According to Meijer et al. (2009), the primary barriers to sustainable renovation are a lack of knowledge and the unconvincing cost-benefit relationship, whereby investors do not always benefit from improved performance. Furthermore, barriers can be found in the market, such as inappropriate products, a lack of experience, and a few best-practice examples.

Another study by Palm & Reindl (2018) provides a more in-depth understanding of barriers in building refurbishment projects and distinguishes between organisational, information or knowledge, behavioural, technical, and financial barriers. Although this study offers a more comprehensive understanding of barriers and includes more categories, it is still consistent with the first study. For instance, organisational barriers, including a fragmented market, lack of time, split incentives, and behavioural barriers, such as inertia, lack of shared objectives, and bounded rationality, have the most significant impact. Financial barriers can also be seen in the lack of profit and value for energy efficiency improvements. Therefore, most of the barriers mentioned above are associated with the fragmented nature of the construction industry and its way of working and a lack of interest when the financial profit is unclear.

Consequently, Baek & Park (2012), Femenías et al. (2018) and Meijer et al. (2009) agree that a solution for the given barriers has to consider the legislative gaps at both national and municipal levels as well as technical and financial gaps while including more practical renovations and demonstration projects.

With all their barriers and enablers, building refurbishment creates the use of significant amounts of materials, primarily used to improve the thermal performance of the building envelope. Therefore, it can be said that carbon emissions originate throughout the whole lifecycle of buildings and can be divided into operational carbon for the use of buildings and embodied carbon from the materials extraction and production, transportation, construction, maintenance, replacement, refurbishments, repair, and end-of-life treatment of buildings. Moreover, these improvements directly result from different policy and industry efforts, influencing about half of the climate impact if a building´s life cycle stems from embodied carbon. Therefore, existing buildings need to enable alteration strategies, allowing them to respond to mitigate climate changes and various occupant requirements while embracing principles of CE by simultaneously reducing both operational and embodied carbon emissions in buildings and creating sustainable structures with prolonged life cycles (Gustavsson & Piccardo 2022; Nußholz et al. 2023; Shahi et al. 2020).

2.4. Circular Economy Design Approaches

This section will further explore design approaches towards implementing CE strategies in building refurbishment practises based on the CE as mentioned earlier frameworks in the built environment. In the study by van Stijn & Gruis (2020) eight requirements for circular design tools are derived from analysing existing circular design frameworks and those are:

1. The first requirement is the system approach, in which the building component is regarded from within its wider system environment.
2. The second requirement is an integral approach, ensuring the design is coherent with other disciplines in the process, including the technical, business, and industrial models.
3. The third requirement indicates that a design tool has to include the relevant circular design parameters.
4. The fourth requirement establishes the need to provide various practical design options for each design parameter.
5. The fifth requirement relates to the circular design tool and its need to relate to the scale levels present in buildings.
6. The sixth requirement involves the circular design tool, which needs to consider approaches oriented towards longer lifespans.
7. The seventh requirement consists of building industry manufacturing techniques, materialisation, supply chain, and financial requirements, which have to be part of the circular design tool.
8. The eight requirements accommodate the design tool's need to accommodate different stages of a design process.

The given requirements can be used in developing the design tool for circular building components or the building as a whole; however, various design approaches need to be considered besides requirements.

Those design approaches need to be seen as an aid in reducing embodied carbon emissions and mitigating climate change. The study by Gallego-Schmid et al. (2020), investigated closing, slowing, and narrowing loop strategies to CE and their relation to climate change mitigation. For example, the study by Gallego-Schmid et al. (2020) found several ways to mitigate climate change for the slowing resource loop strategy:

1. Reuse at the product level, with a focus on Design for Disassembly (DfD), has been seen as a critical solution to facilitate material reuse, especially if the building´s components are reused in two to three cycles, which can lead to 15% to 21% CO_2 eq—emissions savings, compared with traditional buildings where material replacements take place over 50 to 80 years.
2. Reuse at the sectoral level, which can also be seen as a mitigation of barriers to adopting CE principles in the industry, is followed by the aspect of durability. Durability can be linked to the reuse of building components, where more durable components are able to withstand a larger number of reuses, followed by moving from smaller, single produced elements as bricks to mass-produced, building modules as walls. However, in the case of durability as a strategy, attention needs to be paid to the number of replacements and repairs, as that is a critical factor, that can affect GHG emissions.
3. Refurbishment of existing building stock, and this strategy can achieve potential reductions in resource consumption and GHG emissions by extending building lifespans. Time and space related decisions involved in the refurbishment of a building have a significant impact on the building´s life cycle GHG emissions, and although this strategy cannot be seen as a not zero-carbon, it still has relative environmental benefits compared to demolishing a building and construction a new one in its place.

Like this study, the study by Stijn (2023), found additional strategies with the ability to slow lops, such as design for ease of maintenance and repair, followed by upgradability and adaptability. However, in this study, design for disassembly and re-assembly have been seen as a part of both slowing and closing loops, as design in which buildings´ components, parts and materials can be separated and reassembled easily. Both studies by Gallego-Schmid et al. (2020) and Stijn (2023), agree that in the case of mitigation climate change, the closing resource loop strategy is upcycling. Therefore, upcycling can be defined as a recycling process in which used materials are converted into something of the same or higher value and quality in their second life. This process produces GHG savings compared to landfilling and natural extraction. Although there seem to be barriers to upcycling, authors argue that buildings´ components need to be designed for both technical cycles or designed in such a way that the materials can be continuously and safely recycled into new materials, parts, or components and for biological cycles, designed with safe and healthy materials, that create and nourish natural systems across their life cycle.

Finally, narrowing resource loops is needed to mitigate climate change. In the study by Stijn (2023), it is suggested that in the case of narrowing resource loops, it is necessary to design for material reduction so that the amount of materials, virgin or with a high environmental impact, is reduced in the building component, during manufacturing, construction and use. Additionally, the same study suggests that another strategy with the idea of narrowing resource loops is designed for energy reduction or that the amount of energy used, or the environmental impact of the energy used during manufacturing, construction and use of the building is reduced.

Moreover, the study by Gallego-Schmid et al. (2020), agrees with the abovementioned study. It complements the narrowing resource strategy with the example in which six types of indoor floor coverings are compared, where the inorganic floor coverings, such as ceramics and natural stone, gave the highest emissions savings across the life cycle due to low maintenance requirements, despite being emissions intensive during the manufacturing stage. Hence, its finding emphasises the importance of analysing the entire life cycle. On the other hand, not only choice of materials can cut GHG emissions, but also cutting energy consumption by implementing technological and architectural passive house measures, which can help to reduce the lifecycle carbon footprint of a building significantly, which is especially important for building refurbishment of existing building stock. Additionally, the choice of construction method can lower carbon emissions, such as modular buildings and substitution of cement by lower carbon-intensive materials. The relationship between closing, slowing, and narrowing loop strategies and circular design approaches, is shown in Table 1.

Table 1 The relationship between closing, slowing, and narrowing loop strategies and circular design approaches (Source by Gallego-Schmid et al. (2020) and Stijn (2023)).

Loop strategy	CD approach	Definition
Narrowing loops	Design for material reduction	Design for material reduction so that the amount of materials, virgin or with a high environmental impact, is reduced in the building component, during manufacturing, construction and use.
	Design for energy reduction	Design for energy reduction or that the amount of energy used, or the environmental impact of the energy used during manufacturing, construction and use of the building is reduced, by additional technological and architectural measures.
Slowing loops	Reuse at the product level	Design for disassembly, or design so building's components can be reused in two or three cycles
		Substitute of certain materials with other materials with higher carbon emissions saving potential.
	Design for standardization and compatibility	Creating building components with parts or interfaces that also fit other building components.
	Design for ease of maintenance and repair	Designing for maintenance and repair allows building components to be kept in solid condition and repaired when necessary.
	Design for upgradability and adaptability	Designing building components to allow for future modifications and improvement to prevent premature obsolescence.
Closing loops	Upcycling	Design for technical cycles or designed in such a way that the materials can be continuously and safely recycled into new materials, parts, or components.
		Design for biological cycles or designed with safe and healthy materials, that create nourish natural systems across their life cycle.

2.5. Circular economy assessment tools in building refurbishment practises

This section will present different tools for assessing circularity in building refurbishment. According to Corona et al. (2019), circularity assessment tools measure the burden or value created by a circular system. Moreover, these tools are usually applied to determine which CE strategy should be favoured, or whether the adoption of a CE strategy would increase the sustainability of an existing system. Today, most of the given assessment tools in the literature provide burden-based indicators, or value-based indicators, and based on the economic value added or the extended utility of the analysed system.

2.5.1. LCA-Life-cycle assessment

As already mentioned, in Europe, buildings contribute to 40% of final energy consumption and account for almost the same share of energy related GHG. For that reason, initiatives such as the “Renovation Wave” (European Commission, 2020b) in Europe have been developed with the goal of reducing the operational energy use of existing buildings. Optimizing the energy performance of existing buildings will create additional embodied emissions related to manufacturing, transporting, and replacing the materials added to refurbishment projects (Zimmermann et al., 2023).

Whole-life carbon is typically determined through the standardized LCA, which is commonly used to assess the environmental impacts of buildings. A growing number of scientific publications have been focusing on the LCA of building renovations, usually with a focus on improving their energy performance. In those case studies where LCA is carried out, the improved energy performance typically results in net environmental and GHG savings over the building´s life cycle. The most significant GHG savings have been found by improving the thermal insulation level of the building envelope, followed by upgrades of the heating system. (Zimmermann et al. 2023).

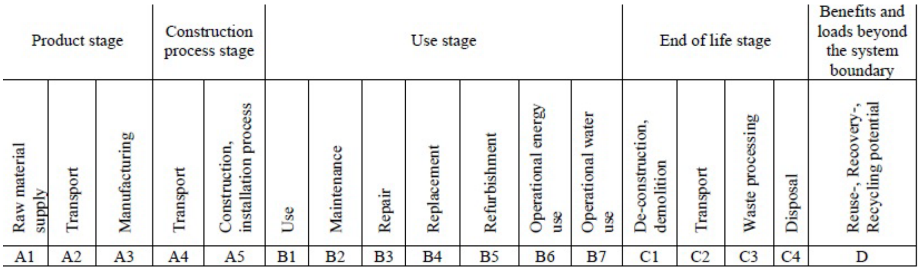
Although measuring whole-life carbon emissions is necessary, especially for refurbishment projects, it still raises many limitations. One of those limitations is legislation regarding life cycle stages in LCA analysis.

According to (Zimmermann et al., 2020), the European standard EN 15978 from CEN TC 350 describes the calculation method to assess the environmental performance of buildings. The life cycle stages included in LCA for buildings is shown in Figure 2. The standard describes the method for “new and existing buildings and refurbishment projects”; however, the method for existing buildings is not very clearly defined. In building practice, the considerations about the future development of an existing building will concern the following options:

1. Preservation.
2. Renovation
3. Demolition and new construction (Zimmermann et al., 2020).

Renovation is addressed in the standard through the “refurbishment" module B5. When new buildings are assessed, the impacts from renovation should be allocated to module B5. This module includes impacts from production of new building components (input materials) as well as transportation and construction. It also includes EOL stages of replaced building components (output materials). Renovation in module B5 is scenario-based because it happens in the future. However, when the renovation is done today on an existing building, the scope changes. The standard addresses this, stating that for buildings that are renovated, and where there has been made no previous assessment; a new LCA should be made (Zimmermann et al., 2020).

In this case, environmental impacts and aspects of materials and installation processes are allocated to module A1-A5, as the renovation is no longer a scenario in the future, but something that happens today. With the input materials allocated to stage A, it is implicit that the output material of the existing building is not included in the framework. Thus, the approach will not give the complete impact from the building's remaining life cycle, but only the impacts from the new materials in the renovation action itself (Zimmermann et al., 2020).



Product stage			Construction process stage		Use stage							End of life stage				Benefits and loads beyond the system boundary
Raw material supply	Transport	Manufacturing	Transport	Construction, installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction, demolition	Transport	Waste processing	Disposal	Reuse-, Recovery-, Recycling potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

Figure 2. Life cycle stages of the building (Source by Zimmermann et al. 2020).

In the same study by Zimmermann et al. (2020), authors proposed the LCA framework, which can be used especially for refurbishment projects. In that case, for the refurbishment scenario, action is taken today, meaning that some of the existing products are demolished and processed, while other new products are included in the building. Moreover, in this case some of the products are preserved and continues directly into stage B. The refurbishment scenario therefore includes the initial C1D1 and A stages as well as the remaining stages, and it is shown in Figure 3.

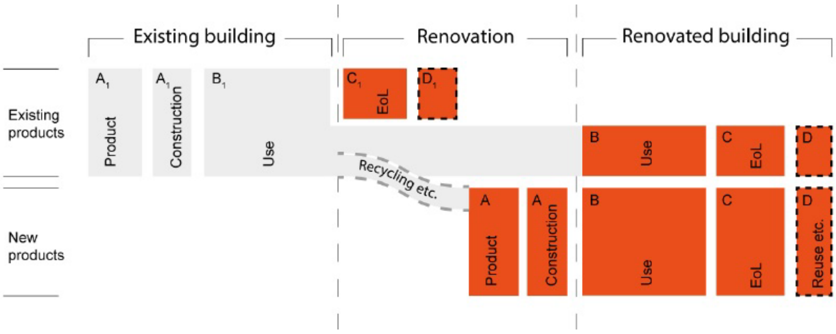


Figure 3. Framework for the refurbishment scenario, where existing buildings act as the starting point (Source by Zimmermann et al. 2020).

2.5.2. LCA and Allocation Approaches for CE Strategies in Building Refurbishment

LCA can be an excellent method to analyse buildings´ components and single life cycles; however, it needs to be considered through a multi-cycling system perspective to be used as a tool in adopting CE strategy in building refurbishment practises. This is because CE is operationalised through value retention processes (VRPs), such as reduce, reuse, repair, refurbish, recycle, and recover, some of which result in re-loops. The CE concept not only considers one re-loop but a sequence of multiple re-loops, creating cascading systems, buildings, components, and materials that can potentially have different and multiple uses and life cycles. Dividing burdens between cycles is a widely discussed question in LCA, and there is no single accepted approach among many different allocation approaches in the literature. However, the results of the LCA, and consequently CE strategies, may be influenced by the choice of allocation approach (Eberhardt et al. 2020). Therefore, five allocation approaches from the literature will be further developed:

1. The first allocation approach is the cut-off approach, which assumes that the recycled product is made from waste that does not have any economic value. Therefore, the recycled product uses a burden-free feedstock, and the burdens of the recycling activities are allocated to the recycled product. Moreover, this approach is easy to apply and straightforward to communicate because it naturally follows the technical and business boundaries proposed by frameworks (Corona et al. 2019; De Wolf et al. 2020).
2. The second approach is the EOL approach, in which the recycled doesn't get any credit. Those credits are allocated to the producer of the recycled material or to the primary product. Moreover, the allocation of impacts in this approach assumes that building components will be reused after the initial life cycles, and the environmental impacts of production and EOL are only accounted for in the last life cycles, which unfortunately encourages stakeholders to design for downstream reuse (Corona et al. 2019; De Wolf et al. 2020).
3. The third allocation approach is European Commission Environmental Footprint, known as EC EF. This approach was defined to equally allocate the environmental impacts of production and disposal stages in the first and last use cycles, and in the case of built environment, this approach encourages LCA stakeholders to employ reused components in their projects or to construct with the aim of reusing components in future cycles (De Wolf et al. 2020).
4. The fourth allocation approach is the 50:50 approach were the burdens and credits from recycling are shared equally between the primary and recycled products. This approach is appealing in terms

of CE strategies, as it accounts for the number of times a material will be reused and recycled (Corona et al. 2019; Eberhardt et al. 2020).

5. The fifth approach is linear degressive, known as an LD approach, which enables distributing environmental impact over entire cascades of cycles. Moreover, this approach uses a discounting principle, allocating impacts from virgin material production and disposal linearly degressive to all use cycles, allocating the highest share of impact to the cycle where the impact happens. This approach is appealing in terms of CE strategies, as it accounts for the number of times a material will be reused and recycled; although this can be difficult to predict, the LD approach considers changes in material qualities over the cycles (Eberhardt et al. 2020).

It is worth noting that not all allocation methods are equally valuable when it comes to implementing CE strategies in the built environment, particularly in building refurbishment practices. While the presented allocation methods help narrow, slow, and close life cycles regarding CE strategies in the current scenario, some fail to create similar benefits in future scenarios. For instance, the cut-off and 50:50 approaches exhibit mediocre performance when considering future CE scenarios for today's applied materials and focus on reducing current emissions by encouraging secondary material use. Moreover, compared to other approaches, the LD approach is favourable regarding CE strategies. This approach focuses on closed-loop systems; it is simple to use and creates incentives for narrowing, slowing, and closing loops while dealing with infinite numbers of future life cycles and emphasising material quality in that process. Furthermore, a multi-cycling assessment approach is needed in practice to support the transition to a circular built environment. Therefore, based on the study of the given approaches, the CE LD approach is developed, which can be used for known cycles or in combination with LCA for unknown cycles because the current LCA does not include allocation approaches in future scenarios (Eberhardt et al. 2020).

2.6. Barriers and Enablers in the Circular Economy within the Built Environment

Besides relevant circular frameworks and clear guidance, especially in building refurbishment cases, the construction industry faces various barriers. Moreover, according to AlJaber et al. (2023) and Çetin et al. (2021), the barriers that hinder the implementation of circular economy (CE) principles in the built environment can be categorized into six types:

1. Social and cultural barriers, which are also referred to as awareness barriers. This type of barrier arises when stakeholders lack knowledge about implementing CE principles. As a result, they may

miss out on potential economic and environmental benefits, which can lead to a fragmented supply chain with poor communication and coordination between actors.
2. Organisational barriers, where priority is given to the energy transition of the building sector. Despite this, there is still a focus on promoting linear economic principles. Furthermore, the lack of time and human resources to evaluate further CE principles is also a problem.
3. Financial, economic and market barriers, where the high cost of virgin circular and existing recycled materials is evident. Additionally, stakeholders may struggle to create business models for the sustainable development of the built environment. Limited funding for circular projects is also a challenge.
4. Sectoral barriers refer to a lack of overall interest in the construction industry in implementing CE principles. There is also uncertainty about how to approach the treatment of existing buildings and the end-of-life treatment of materials.
5. Technical barriers, where there is a lack of policy and legislation, not just on the state and municipal levels but also within companies. There is also a need for more standardisation and circular design guidelines. Flexibility in building codes and regulations and digital tools that can make this work easier are also lacking.
6. Regulatory barriers, where circularity is not effectively integrated into regulations. There is limited circular procurement and uncertainty regarding future legislation implementing CE principles (AlJaber et al., 2023; Çetin et al., 2021).

The construction industry and energy retrofitting practices face similar challenges in implementing CE principles. A study by Palm & Reindl (2018), which followed the planning and design phase of renovation projects in publicly owned rental companies, identified several common barriers to implementing energy efficiency measures and these include:

1. Market fragmentation, split incentives, and lack of time.
2. Information barriers, such as a lack of clear communication between stakeholders.
3. behavioural barriers, such as a lack of shared objectives, inertia, and bounded rationality.
4. Technical obstacles.
5. Financial barriers, including high investment costs, low value placed on improved energy performance, and fear of financial loss.

Therefore, it can be concluded that the barriers faced in energy retrofitting projects are not significantly different from those faced in the construction industry. Table 2 summarises the most common theoretical barriers, on both larger and smaller scales to adopting CE principles and energy retrofitting projects on existing building stock.

Table 2. The most common theoretical barriers, on both larger and smaller scales to adopting CE principles and energy retrofitting projects of existing building stock (Source by AlJaber et al. (2023), Çetin et al. (2021) and Palm & Reindl (2018)).

Category	Sub-category
Social and cultural barriers	Lack of knowledge
	Fragmented supply chain
	Resistance from stakeholders
	Lack of clear communication between stakeholders
Organizational barriers	Giving higher priority to other issues
	Lack of time
Financial barriers	High purchasing cost of new circular materials
	High purchasing cost of recycled materials
	High purchasing cost of virgin materials
	Lack of clear business models for sustainable development
	Lack of funding
	Fear of financial loss
Sectoral barriers	Uncertainty in buildings´ components end-of-life treatment
	Complexity of projects
Technical barriers	Lack of policy and legislation
	Lack of standardization and circular design guidelines
	Lack of flexibility in building codes and regulations
Regulatory barriers	Limited circular procurement
	Uncertainty regarding future legislation implementing CE principles

Although all barriers to circular buildings are important, it is necessary to identify the most common ones in the literature and practice. According to AlJaber et al. (2023), technical barriers are the most frequently cited in literature and practice, followed by financial and market barriers. Social and cultural barriers, also known as awareness barriers, emphasize the importance of knowledge sharing among different actors in the construction industry.

Organizational or implementation barriers demonstrate stakeholders' resistance to change and how that plays a significant role in the transition towards more circular buildings. Social or sectoral barriers come next, and finally, regulatory, or promotion-related barriers. On the other hand, Çetin et al. (2021), investigate the barriers mentioned above in the context of implementing CE principles in housing stock, mainly managed, and owned by the social housing organisation in the Netherlands. According to their study, the most pressing five barriers appear to be:

1. Higher priority in other issues
2. Operating in a linear system.
3. Lack of awareness, knowledge, and experience with CE.
4. High purchasing cost of circular materials.
5. Unclear business case (Çetin et al., 2021).

As can be seen from both studies by AlJaber et al. (2023) and Çetin et al. (2021) barriers, that influence adapting towards circular transition in the built environment are economic, organisational and awareness barriers, followed by technical and regulatory barriers. Besides investigating barriers, AlJaber et al. (2023) and Çetin et al. (2021) focused on investigating enablers as answers to found barriers, which can help transition towards implementation of CE principles in the built environment.

Those enablers can be organised in the same order as the barriers mentioned above:

1. Social and cultural enablers, or awareness enablers, such as the importance of leadership and collaboration between all actors involved in the project, are followed by investing in CE training, education, and workshops.
2. Organisational enablers, promoting the importance of circularity in building within organisations, together with other high-priority strategies to create more sustainable and resilient buildings.
3. Financial, economic, and market enables, such as promoting lower costs of circular materials (new and existing), as well as financial incentives and clear business models that will support this transition.
4. Sectoral barriers, focus on developing industry standards for recycled materials and promotion of best cases in practice.
5. Technical barriers, the development of tools and guidelines, and the development of digital technologies can help facilitate a more accessible and faster transition.
6. Regulatory enablers, legislation on state and municipality levels, that promote transition as well as policy support with further states agreement on circular economy (AlJaber et al., 2023; Çetin et al., 2021).

Moreover, it can be said, that the most powerful ways of mitigating CE implementation barriers are to create legislative supportive policies, as well as financial incentives and digital tools that can help to mitigate barriers in earlier phases of design processes. Furthermore, most of the technical and organizational challenges that arise in these types of projects are related to the end-of-life treatment of building components. This is because building systems, elements, and components are interconnected and cannot be separated for partial recovery or disassembly. As a result, very few parts can be reused or recycled (Fernandes & Ferrão 2023). Table 3 summarises the most common theoretical enablers, on both larger and smaller scales or on the industry level, to adopting CE principles and energy retrofitting projects of existing building stock.

Table 3. Most common theoretical enablers, on both larger and smaller scales or on the industry level, to adopting CE principles and energy retrofitting projects of existing building stock (Source by AlJaber et al. (2023), Çetin et al. (2021) and Fernandes & Ferrão, 2023)).

Category	Sub-category
Social and cultural enablers	Importance of leadership
	Collaboration between all stakeholders
	Investment in CE training, education, and workshops
Organizational enablers	Promoting importance of circularity of building within organisations
	Promoting high priority strategies to create more sustainable and resilient buildings
Financial enablers	Promoting lower cost of circular materials
	Promoting financial incentives
	Promoting circular business models
Sectoral enablers	Developing industry standard for recycled materials
	Promotion of best cases in practice
Technical enablers	Development of tools and guidelines for adopting CE principles
	Development of digital technologies
Regulatory enablers	Promoting legislation on state and municipality levels

3. Embracing CE principles in Energy retrofitting

3.1. Energy retrofitting strategies for lowering operational and embodied carbon emissions

Residential buildings account for a large share of the total energy usage in the European Union. Improving energy efficiency in the older part of the existing housing stock has become central to reducing energy use in the building sector overall. Space heating remains the largest share of energy use in buildings, particularly in regions with cold climates, representing 60-80% of total energy use. However, Sweden has a unique energy system, where the electricity supply is primarily from renewable sources and nuclear power. Almost 90% of Sweden's multi-family buildings rely on city-based district heating (DH) systems. Many studies suggest that a large share of the existing building stock in Sweden, has a relatively good standard. However, most buildings did not have common energy efficiency measures applied. Renovating buildings can effectively decrease the need for space heating. Various studies have demonstrated significant energy-saving potential by enhancing the building envelope's thermal quality, including the façade, roof, and windows. Additionally, implementing energy-efficient measures in the spaces between heated and non-heated areas and installing ventilation recovery systems are standard practices in energy retrofitting (La Fleur et al. 2017; Ramírez-Villegas et al. 2019).

Those extensive renovation measures are known as deep renovation measures. Deep renovation with energy savings between 60% and 90% is necessary to reach the decarbonisation targets for 2050. A deep renovation typically adopts a holistic approach, viewing the renovation as a package of measures working together, as opposed to moderate renovation, involving 3-5 improvements resulting in energy reductions in the range of 30-60%. The building envelope becomes the most critical part when it comes to energy-efficient building, both for new construction and refurbishment. The significance of the building envelope is justified, as the energy consumption is directly related to it. Usually, deep renovation includes measures such as insulation of walls, roof and cellar ceiling, upgrade of the windows, elimination of thermal bridges and upgrades of the ventilation system (Konstantinou 2014).

As mentioned in Chapter 2., Literature Overview, the whole-life carbon emissions of buildings can be divided into operational and embodied carbon emissions. However, in the case of deep renovation practises of existing buildings, higher value is usually given to lowering existing operational carbon emissions from heating, cooling, and lighting than lowering future embodied carbon emissions from material choices. Therefore, it is necessary to analyse energy efficiency measures for building refurbishment to better understand their effects on overall carbon emissions during various lifecycle stages of the building.

3.2. Circular design strategies for lowering operational and embodied carbon emissions

Besides deep renovation measures to lower primarily operational carbon emissions from the building's use stage, it is necessary to adopt circular design strategies that can be applied to building refurbishment practises. These strategies aim to minimise the embodied carbon and waste of materials used in the renovation process, promoting a more sustainable and resource-efficient approach to building retrofits.

Drawing on the CD strategies of narrowing, slowing, and closing resource loops and an extensive study by Stijn (2023) a technical model was developed with relevant design parameters to promote circular building components in building refurbishment practices. While many studies recommend considering not just technical components but also industrial and business models, this study focused specifically on building refurbishment practices for existing structures, aiming to develop more accessible and easier-to-implement design guidelines that various stakeholders can widely adopt in the construction industry to improve the energy efficiency and sustainability of the built environment.

The technical model was developed based on several key parameters. The first key parameter was the choice of materials. Materials used in building the refurbishment of the case study were divided into biological and technological sub-parameters. Second, the energy usage during the building's operational phase was examined. The same was employed in the case of heating, too. Then, the existing construction system, improved by additional components, was also analysed to determine its alignment with CD approaches. Measuring the inflow of imported materials, virgin and non-virgin, was necessary to track and manage their use across future lifecycles of the building components more effectively. Following the measurement of imported materials, they were further distinguished by the specific lifecycle stage at which they were introduced into the overall system. Finally, the CD strategies of narrowing, slowing, and closing resource loops were applied based on the previously identified requirements and parameters. Table 4 shows the technical model based on crucial CD parameters.

Table 4. The technical model based on key CD parameters (Source by Stijn (2023)).

Parameter			Sub-parameter			
Number	Parameter		Number	Sub-parameter		
P1	Materials/ resources		P 1.1.	Biological materials	P 1.1.-1	Renewable material
					P 1.1.-2	Safe material
					P 1.1.-3	Low impact material
			P 1.2.	Technical materials	P 1.2.-1	Durable material
					P 1.2.-2	Virgin material
					P 1.2.-3	Non-virgin material (reused)
P2	Energy		P 2.1.	Type of energy (in use)	P 2.1.-1	Gothenburg DH system
					P 2.1.-2	Gothenburg city electricity
P3	System architecture		P 3.1.	System elements	P 3.1.-1	Building
					P 3.1.-2	Building component
					P 3.1.-3	Building sub-component
					P 3.1.-4	Parts
					P 3.1.-5	Materials
P4	Amount of elements		P 4.1.	Amount of elements/resources	P 4.1.-1	Number of system elements
					P 4.1.-2	Amount of resources (kg, m^3, kWh)

P5	Time		P 5.1.	Amount of lifecycles	P 5.1.-2	Single lifecycle
					P 5.1.-2	Multiple lifecycle
			P 5.2.	Expected lifespan	P 5.2.-1	Short
					P 5.2.-2	Medium
					P 5.2.-3	Long

P6	Lifecycle stage		P 6.1.	Lifecycle stage of building component	P 6.1.-1	Introduction
					P 6.1.-2	Growth
					P 6.1.-3	Maturity

P7	Circular design approaches	Narrowing loops	P 7.1.	Design for material reduction	P 7.1.-1	Apply low impact or reused materials
					P 7.1.-2	Reducing materials in production
					P 7.1.-3	Reduce material in building component
			P 7.2.	Design for energy reduction	P 7.2.-1	Energy efficiency in use phase
					P 7.2.-2	Use renewable energy sources

		Slowing loops	P 7.3.	Design for attachment	P 7.3.-1	Design for easy use
			P 7.4.	Design for durability	P 7.4.-1	Consider future scenarios
					P 7.4.-2	Select for appropriate lifespan
					P 7.4.-3	Use durable materials

				P 7.4.-4	Design so building components can withstand repetitive assembly and disassembly
				P 7.4.-5	Reduce coated and painted components
				P 7.4.-6	Design for simple use of building component
		P 7.5.	Design for standardisation and compatibility	P 7.5.-1	Product/building standardisation
		P 7.6.	Design for ease maintenance and repair	P 7.6.-1	Make design accessible
				P 7.6.-2	Standardize design fit
				P 7.6.-3	Modular design
				P 7.6.-4	Reduce variations in building component lifespan
		P 7.7.	Design for upgrades and adjustments	P 7.7.-1	Separate building components into shearing layers
				P 7.7.-2	Plan for future scenario design
				P 7.7.-3	Use standard components and parts to ease updates
		P 7.8.	Design for disassembly	P 7.8.-1	Methods that will allow disassembly without damage
				P 7.8.-2	Standardized and modularised components
				P 7.8.-3	Avoid non-solvable adhesives

	Closing loops	P 7.9.	Design for upcycling (recycling)	P 7.9.-1	Separate building parts at material boundaries
				P 7.9.-2	Use recycling compatible materials
				P 7.9.-3	Use components and parts easy for re-loops

4. Methods

The study is based on a qualitative research approach. The study focuses on finding a balance between reducing operational and embodied carbon emissions by applying CE design approaches during the energy retrofitting of a residential building. Regarding energy calculations, the proposed approach is compared to the existing building.

However, the LCA analysis is divided into two analyses as a broader perspective is considered, comparing the case study to the two scenarios. In the first analysis, one is the existing building case, in which no energy retrofitting measures were considered. The other scenario is the business-as-usual (BAU) approach towards building energy retrofitting, which considers applying only virgin materials without reusing and recycling treatments of applied materials. The second analysis is the existing building case, while the other scenario is the CE refurbishment case, which applies only to non-virgin materials.

This approach to the LCA analysis allows it to compare existing operational carbon emissions while better understanding embodied emissions as a product of deep renovation actions. Additionally, the study focuses on the various life cycles of building components to ensure a sustainable and efficient retrofitting process and how each stage influences the overall carbon emissions from the building. This work is based on empirical data collected from the municipal housing company, Familjebostäder, from Gothenburg, including the building plan, the suggested materials in the construction system and the energy report.

4.1. Transmission losses and specific energy use

The case study leans on the energy report provided by the company to determine the energy needs of the building (AFRY 2023). Despite this, it is necessary to calculate the heat transfer coefficients for various parts of the case study to ensure compliance with the CD approaches. The outer walls, the roof, windows, doors, and floors between unheated and heated areas are building parts considered for the case of study energy retrofitting. The material choice for building parts aligns with recommendations from the Swedish National Board of Housing, Building and Planning (Boverket).

The analysis is based on the limitations of the heat transfer coefficient of individual parts and an additional 20% of transmission losses accounted for by thermal bridges to determine the maximum average heat transfer coefficient. These limitations are shown in Table 5.

Table 5. The limitations for the heat transfer coefficient of individual parts (Source by Karlsson Hjorth et al. (2021)).

Heat transfer coefficient of individual building parts	$(W/_{m^2 * K})$
U_i	$(W/_{m^2 * K})$
U_{roof}	0.13
$U_{outer\ wall}$	0.18
U_{floor}	0.15
U_{window}	1.2
U_{door}	1.2

Therefore, it is necessary to establish the heat transfer coefficient for the outer wall and the roof. Both building components contain airspace, and their U values are calculated according to the equation (1) and (2) (Pinteric 2021).

$$R_{tot} = R_{se} + R_a + \Sigma \frac{d_i}{\lambda_i} + R_{si} \tag{1}$$

$$U_i = \frac{1}{R_{se}+R_a+\Sigma\frac{d_i}{\lambda_i}+R_{si}} \tag{2}$$

- $U_i - the\ heat\ transfer\ coefficient\ (W/_{m^2 * K})$
- $R_{se} - external\ surface\ resistance\ (m^2 * K/_W)$
- $R_{si} - internal\ surface\ resistance\ (m^2 * K/_W)$
- $R_a - thermal\ resistance\ of\ airspace\ (m^2 * K/_W)$
- $d - thickness\ of\ material\ (mm)$
- $\lambda - thermal\ conductivity\ of\ material\ W/_{(m * K)}$

On the other hand, the heat transfer coefficient for the floor construction and the basement wall can be calculated using a similar equation; however, the construction is treated as a solid construction. This is calculated according to equation (3) and (4) (Pinteric 2021).

$$R_{tot} = R_{se} + \Sigma \frac{d_i}{\lambda_i} + R_{si} \tag{3}$$

$$U_i = \frac{1}{R_{se}+\Sigma\frac{d_i}{\lambda_i}+R_{si}} \tag{4}$$

- $U_i - the\ heat\ transfer\ coefficient\ (W/_{m^2 * K})$
- $R_{se} - external\ surface\ resistance\ (m^2 * K/_W)$
- $R_{si} - internal\ surface\ resistance\ (m^2 * K/_W)$
- $d - thickness\ of\ material\ (mm)$
- $\lambda - thermal\ conductivity\ of\ material\ W/_{(m * K)}$

Based on the heat transfer coefficient, it is possible to determine the heat loss due to the transmission, which is calculated according to equation (5) (Frederiksen and Werner 2013).

$$Qt = \Sigma\ U * A * \Delta T * t\ (Wh) \tag{5}$$

- $U-the\ heat\ transfer\ coeffeicient\ (W/_{m^2}*K)$
- $A-area\ (m2)$
- $\Delta T-the\ temperature\ difference$ (°C)
- $t-time$ (h)

4.2. CE LD Allocation Approach

To assess the environmental impact of using virgin materials and to distribute that impact across their lifespan, the CE LD allocation approach is used. This method is employed as a supplement to the LCA analysis of the case study to link this method with CE strategies. Figure 4 represents how the CE LD equation for diving the production impacts is derived. The red line represents the virgin material production impacts distribution between the use cycles, where the distribution decreases linear degressively from use cycle 1 to “n”. This distribution was calculated in percentage emissions (Eberhardt et al. 2020).

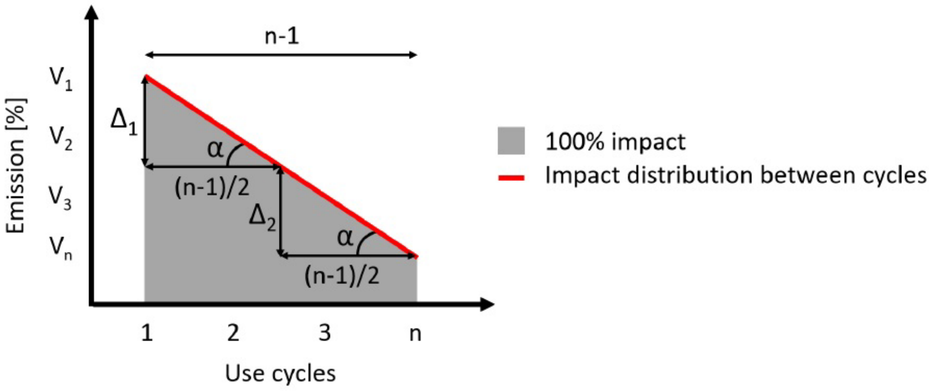


Figure 4. A graphical representation of the CE LD equation for dividing the production impacts (Source by Eberhardt et al. (2020)).

The total impact over the use cycles will always be 100%, thus the average impact in percentage is calculated according to equation (1) (Eberhardt et al. 2020).

$$A_v = \frac{100\%}{n} \tag{1}$$

- $n - number\ of\ cycles$

The coefficient, α, the slope of the graph is calculated according to (2) (Eberhardt et al. 2020).

$$\alpha = \frac{V_1 - V_n}{n-1} \tag{2}$$

- $\alpha - the\ coefficient$
- $V_1 - the\ emission\ from\ \ virgin\ material\ production$
- $V_n - the\ emission\ from\ virgin\ material$
  $prodcution\ allocated\ to\ the\ last\ cycle$

The environmental impact allocated to the first use cycle is calculated according to equations (3), (4) and (5) (Eberhardt et al. 2020).

$$V_1 = A_v + \Delta_1 \tag{3}$$

$$\Delta_1 = \alpha * \frac{n-1}{2} \tag{4}$$

$$V_1 = \frac{100\%}{n} + \frac{V_1 - V_n}{n-1} * \frac{n-1}{2} \tag{5}$$

Similarly, the n cycle is calculated according to equations (6), (7) and (8) (Eberhardt et al. 2020).

$$V_n = A_v - \Delta_n \tag{3}$$

$$\Delta_n = \alpha * \frac{n-1}{2} \tag{4}$$

$$V_n = \frac{100\%}{n} - \frac{V_1 - V_n}{n-1} * \frac{n-1}{2} \tag{5}$$

4.3. Life Cycle Assessment

The LCA study is conducted to determine each renovation measure's environmental impact. The LCA study goals, scope, and boundaries are defined in this section.

4.3.1. Goals and scope of the LCA study

The case study´s LCA purpose is to comprehensively evaluate the carbon impact of each renovation measure and the impact of added building components within CE strategies regarding their global warming potential (GWP).

The first LCA analysis is based on the comparative case study of three scenarios: 1) the existing building scenario, 2) the CE mixed refurbishment scenario or the case study, and 3) the BAU refurbishment scenario. The first scenario is used to determine the impacts of the use phase of the building. In contrast, scenarios two and three are used to determine the overall environmental impact of the building refurbishment practises within the circular and linear systems and the importance of virgin and non-virgin materials used in building refurbishment.

The second LCA analysis is based on the comparative case study of three scenarios: 1) the existing building scenario, 2) the CE mixed refurbishment case or the case study, and 3) the CE reused refurbishment scenario. This analysis's CE reused refurbishment scenario aligns with CE strategies and CD approaches. All applied materials are non-virgin in accordance with the case study. In this way, it is possible to determine how embodied emissions from the initial production and construction of materials affect overall carbon emissions.

The analysis provides insights to construction industry professionals on reducing the GWP of building components while decreasing the operational

GWP. It also introduces the concept of future life cycles of these components. The functional unite in the LCA study is $^{kgCO_e^2}/_{m^2}$.

4.3.2. System boundaries of the LCA study

The LCA´s system boundaries align with those from NollCO2 (SGBG 2023), with a few exceptions. The NollCO2 is built upon the European EN 15978:2011 standard. The life cycle stages considered for the analysis are shown in Figure 5.

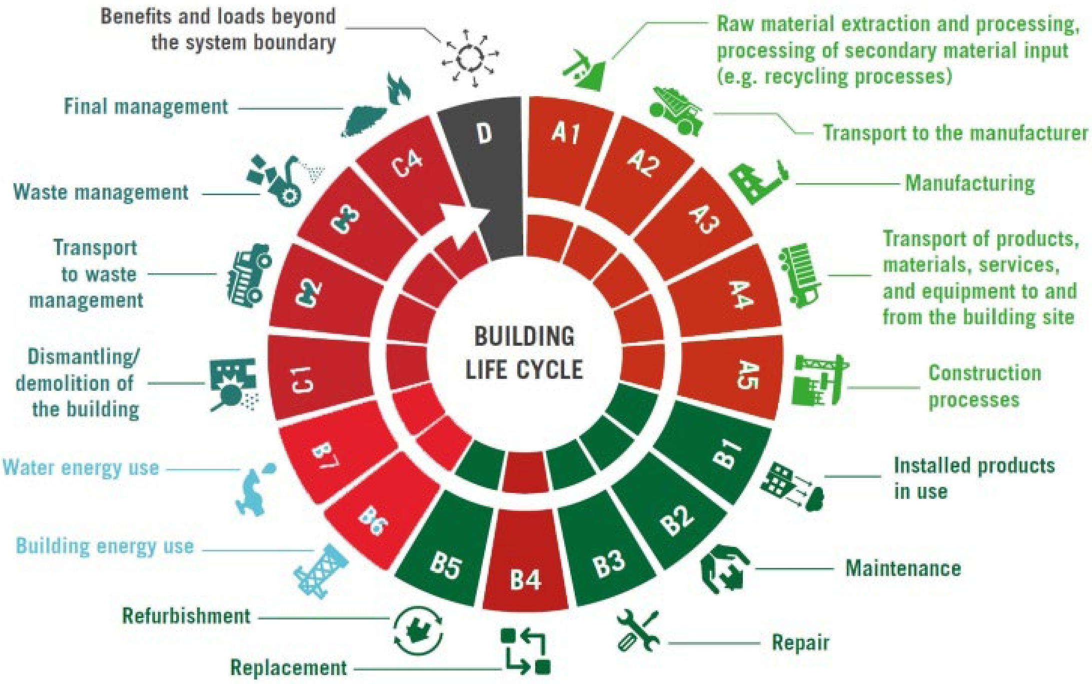


Figure 5. Life cycle stages considered in the study, according to the standard EN 15978:2011 (Source by Sweden Green Building Council (2023)).

The NollCO2 standard includes $A_1 - A_5$ modules of the LCA. For the existing building scenario, there is no contribution from this module. In the other two scenarios, extraction, supply, and installation of virgin materials include all steps of this module, while non-virgin materials include only $A_4 - A_5$ modules. Further, the NollCO2 standard partially includes modules of the stage B, neglecting modules $B_1 - B_3$, as it assumes that these stages have a small climate impact in relation to other sub-modules of this stage. This standard also neglects the EOL stages, $(C_1 - C_4; D)$, assuming Sweden will have fossil-free electricity production by 2045. Since NollCO2 has a calculation period of 50 years, buildings which use this standard will have their final disposal as soon as 2070, which means that climate impacts from these stages will be zero. On the other hand, in the case study and additional scenarios, the C stage is included in the LCA study. The D stage is explained partially through the LCA analysis and on theoretical premises on the final disposal of certain materials back into the biosphere values (see Appendix A: p.1).

The system boundary of the study is limited to the energy retrofitting measures applied in the case study and does not include any other construction work inside or outside the case study. Moreover, the study considers the existing building and the common refurbishment practises, demonstrating how they can contribute to the potential circularity of materials. The climate impact includes materials used in the building components, which are also considered part of energy retrofitting analysis.

The reference study period (RSP), according to the LCA standards, is aligned with the service life of the building, and it is usually from 50 to 100 years. However, in the LCA study which aligns with the CE strategies, the reference study period and what happens when, is more precarious to determine (Stijn 2023). In this case study, besides aligning with CE strategies, the RSP, was assumed based on the RSP period from NollCO2 (SGBG 2023), which is 50 years, and this period stars when the refurbished building is put in operation.

4.3.3. LCA Limitations

The LCA analysis of the study involves certain limitations and simplifications. Specific building components which were not part of energy retrofitting of the case study are avoided, and stage impact values are obtained from generic LCA data. Furthermore, as the LCA does not directly evaluate CE strategies, the CE-related calculations were supplementary and remained at a theoretical level.

5. Case study

The case study is based on the project transforming existing retirement homes into multi-family apartment buildings, in collaboration with the municipal housing company in Gothenburg, Familjebostäder. The project aims to lower carbon emissions from existing buildings by at least 50% by adopting CE strategies in building refurbishment practises. This aligns with the chosen building refurbishment strategy of the case study.

The primary goal of the building refurbishment strategy was to improve the energy efficiency of the existing building by implementing deep renovation measures that directly influence the energy performance of the existing building and excluding all internal changes that were part of the integrated building refurbishment process. The energy performance calculations included the new building's function from the retirement home to a multi-family apartment building, where twelve new apartments were added, including a previously unheated attic; however, any additional internal changes were part of the building refurbishment process but not a part of this study.

The project is in the neighbourhood of Fjällbo Park, in Gothenburg, and consists of 3 buildings, Hus F, D, and E. All buildings functioned as retirement homes and will be converted into multi-family apartment buildings. They were built in the 1930s and underwent significant refurbishment in the 1990s. However, their function remained unchanged. Hus D and E will undergo minor renovation. In contrast, Hus F will undergo deep renovation, and therefore, it is more suitable for the analysis of the influence of CE strategies on lowering operational and embodied carbon emissions in energy retrofitting of existing buildings.

Hus F is built in lightweight concrete with a brick frame, minimal existing insulation, and no balconies. The building has four stories, including a basement and an attic, with a ceiling height of approximately 2.5 m. Prior to converting to a multi-family apartment building, auxiliary facilities were located on the ground floor to support the function of the building, while studio apartments for residents were located on the first floor. In the case of the original building, the basement and the attic were used for storage space and maintenance needs. Moreover, the building has the primary orientation of east and west, with identical facades and most windows allocated on these sides and entrances. The north and south facades are identical but with fewer windows, with two windows distributed per floor. The thermal demand of the building is satisfied by the local DH system, and a connection to the power grid covers its electrical consumption. Figure 6 shows the proposed case study, Hus F.

Figure 6. The proposed case study, Hus F.

5.1. Description

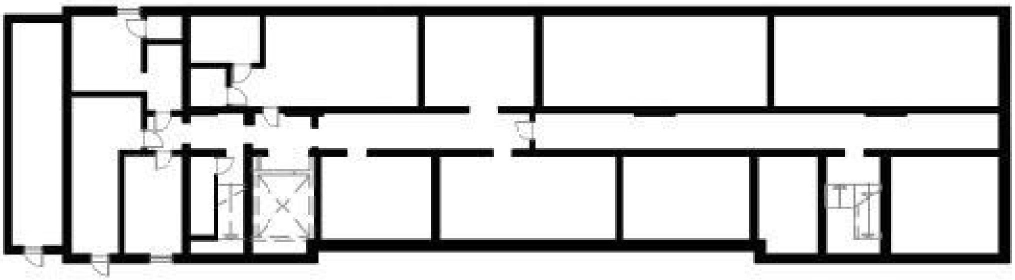
Floorplans of the unchanged function of the existing building can be seen in Figure 7, while the properties of the building are shown in Table 6. Since the existing building envelope was built with a minimal insulation layer, it is necessary to improve the heat transmission coefficient with additional insulation layer. This approach consisted of adding the external layer of the second façade to the existing building with additional layers of insulation and different finishing layers, which aligned with the CD approaches. The main advantage of this strategy was that thermal bridging was solved along with increasing the thermal resistance of the envelope (Konstantinou 2014).

Further, the roof, as a part of the building envelope, was treated in the same way as the façade, while the previously unheated attic was upgrade to the heated one. Moreover, balconies were added to primarily improve the overall quality of each unit in terms of the improved building envelope, light, and views (Shahi et al., 2020). Additionally, all existing window openings, except for additional balconies, remained the same size to minimize material waste and were replaced with new windows with better performance. In contrast, entrance doors and windows remained but with improved performance, so the architectural integrity of the building is preserved. As a part of this building refurbishment package, the barrier between the heated and non-heated areas of the building, in this case, the ground floor and the basement, were included in the energy calculation and align with the CD approaches regarding the material choice. Existing the exhaust and supply air ventilation with heat recovery system (FTX), and air flow of 0.35 $l/(s * m^2)$, based on the given energy report (AFRY, 2023), was replaced. The specific fan power (SFP) for the return air ventilation was set at 2.5 $^{kW}/_{(m^3 * s)}$, and the air leakage rate is 1.4 $l/(s * m^2)$, also based on the given energy report. The building is connected to the DH system, which also covers domestic hot water (DHW) needs of 25 $^{kW}/_{(m^2 * year)}$, according to the energy report.

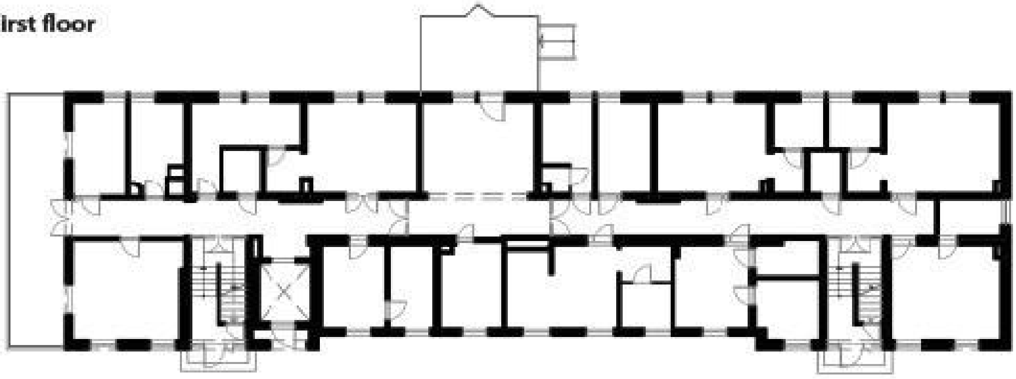
Table 6. The properties of the existing building (Source by AFRY (2023)).

General information	
Description	Value
Location	Gothenburg
Ventilation ($^{l}/_{s * m^2}$)	/
Ventilation system	FTX CAV
SFP ($^{kW}/_{(^{m^3}/_{s})}$)	<2.5
Heating setpoint ($°C$)	21
Heating system	District heating
Construction	
Description	Value
Length (m)	43.40
Width (m)	12.30
Number of floors	1+2+1 (including the basement and the attic)
A_{temp} (m^2)	1857
Wall area (m^2)	688.20
Wall thickness (m)	0.40
Wall U value ($^{W}/_{m^2 * K}$)	0.70
Roof area (m^2)	745.00
Roof thickness (m)	0.24
Roof U value ($^{W}/_{m^2 * K}$)	1.20
Floor above basement (m^2)	432.00
Floor above basement thickness (m)	0.35
Floor above basement U value ($^{W}/_{m^2 * K}$)	0.35
Window U value ($^{W}/_{m^2 * K}$)	2.70
Window area (m^2)	131.46
Door U value ($^{W}/_{m^2 * K}$)	2.40
Door area (m^2)	35.28
U value mean ($^{W}/_{m^2 * K}$)	1.13
Energy demands	
Household electricity $\left(^{kWh}/_{m^2}\ per\ year\right)$	7
Domestic hot water (DHW) $\left(^{kWh}/_{m^2}\ per\ year\right)$	25
Heat demand, including system losses $\left(^{kWh}/_{m^2}\ per\ year\right)$	90
Total building energy use $\left(^{kWh}/_{m^2}\ per\ year\right)$	122

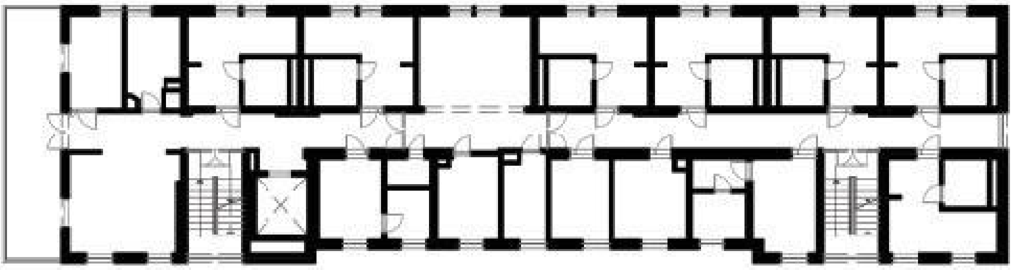
Ground floor



First floor



Second floor



Attic

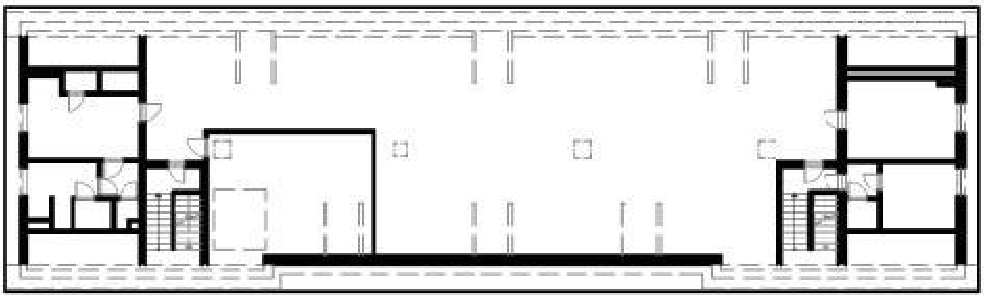


Figure 7. Floorplans of the unchanged function of the building.

5.2. Energy retrofitting measures

This section explains the deep renovation measures considered in the case study. The applied measures are based on CE strategies and include adding insulation to the outer walls, replacing and maintaining existing windows, minimising thermal bridges, and replacing the existing ventilation system with a better-performing one. By addressing these issues, energy retrofitting will improve the building's thermal performance while contributing to better indoor air quality, overall user comfort, and reduction in energy consumption.

5.2.1. Façade and roof

This study focused on reducing the U_{mean} value of the building façade by applying CD approaches. As a result, the additional external layer was added on the façade, which included timber frame elements with incorporated window openings, insulation infill and ventilation facade as a finishing layer. In the case of insulation infill, EPS insulation as a conventional insulation material was considered. The study by Füchsl et al. (2022) analysed the environmental impact of conventional and non-conventional insulation materials. In this study, EPS insulation showed a similar environmental impact to conventional insulation materials, although more environmentally friendly than XPS and PUR. On the other hand, besides its convenience, this material was considered because of its potential reuse and recycling.

Ventilated facades, also called rain-screen systems or dry-cladding systems, comprise the outer skin, the air cavity, the timber frame with an insulation infill layer in this case, and the existing backing wall that frequently includes an insulating layer. The outer skin or panel is called the 'rain-screen', as it forms the primary rain barrier. However, it does not prevent air passage through open joints between the panelling components. An air gap is needed to prevent water from crossing the gap and penetrating the insulation or the backing wall. Depending on the design, the air gap provides ventilation and may provide pressure equalisation across the outer skin. Any water penetrating the cavity is drained away (Konstantinou 2014).

In this way, the additional layer of façade not only improved the energy performance of the existing building but also applied CE strategies for slowing and closing material loops. The façade design was based on the study of Stijn (2023), the Plug and Play façade, which combined CD options to slow and close future cycles. The façade was modular, with standard-sized façade panels attached to insulation modules with click-on connectors that allow repairs and adjustments of the façade and the reuse of parts after its lifecycle. Moreover, materials are recycled and recovered at the EOL of the modules. The model of the façade design is shown in Figure 8.

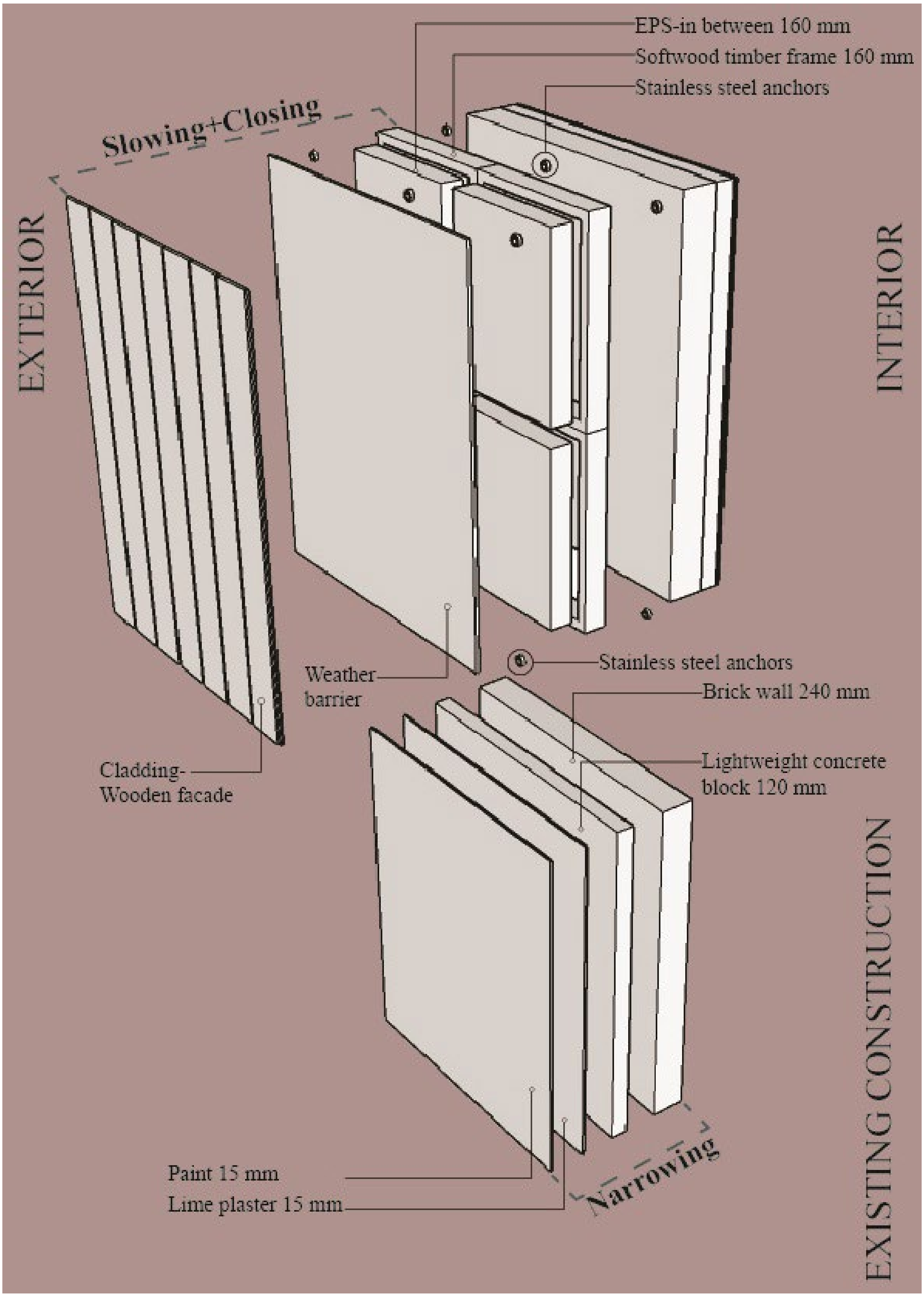


Figure 8. The model of the façade design.

A similar approach aligned with the CE strategies, which were applied to the façade design, was applied to the building refurbishment of the roof, followed by upgrading the existing unheated attic to space with additional four apartments. In this case, an additional layer of needed insulation was added between the existing rafters which were treated as a timber frame, strengthening the existing roof construction and achieving desired U_{mean} value by adding internal space for additional insulation layers. The roof design model is shown in Figure 9.

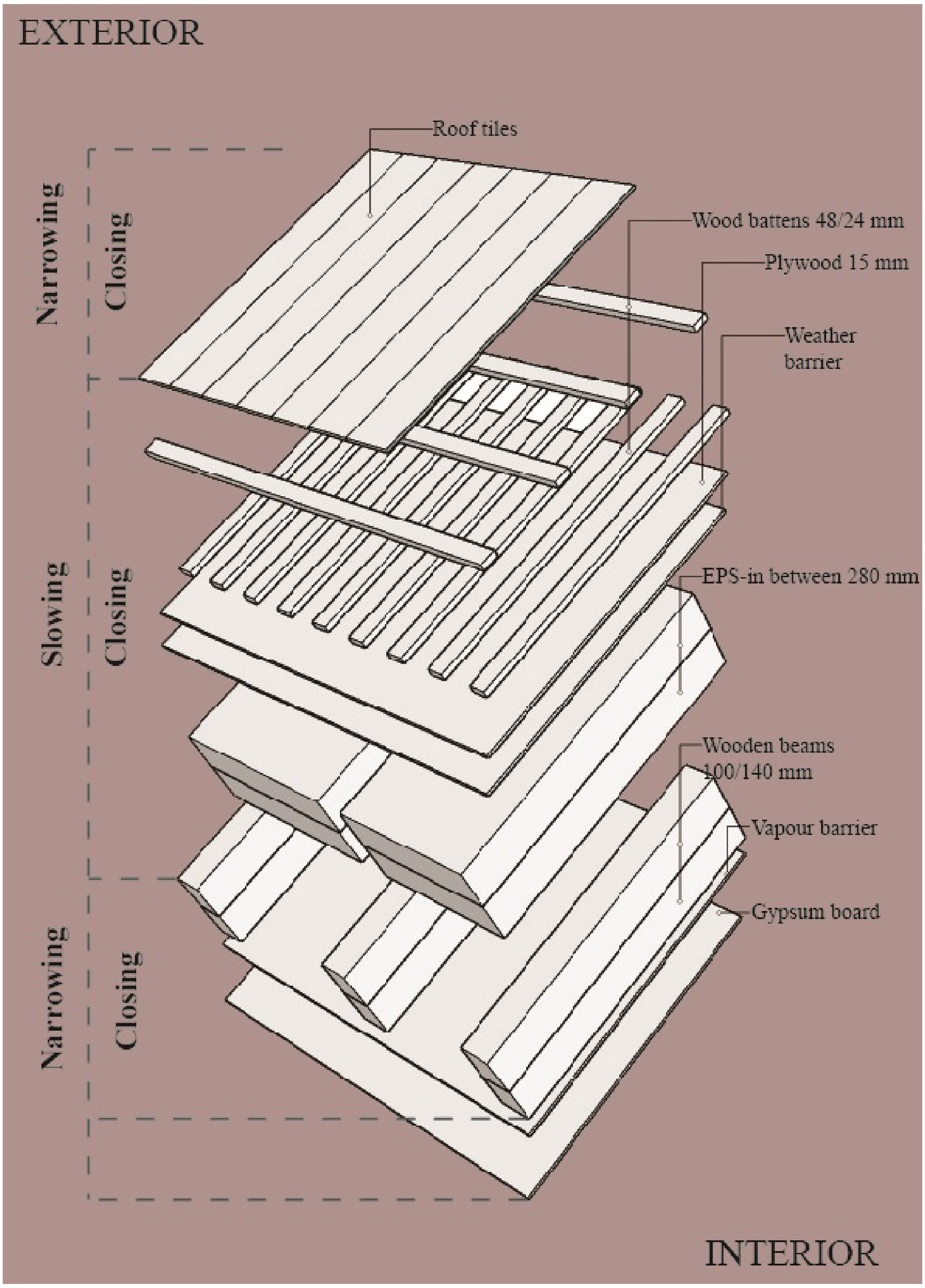


Figure 9. The model of the roof design.

5.2.2. Windows and doors

Window is a key component to energy-efficient buildings. They typically account for about 30–50% of the transmission losses though the building envelope, even if their area fraction of the envelope is far less. Given that over 85% of glazed area in Europe's buildings are made of inefficient products whereas six to eight times more energy-efficient exist, there is big room for improvement in the windows' performance of the housing stock (Konstantinou 2014).

With the aim of the study already mentioned, to improve the energy performance of the existing building, it was necessary to replace the existing windows, the typical 2-layer with insulating glass made of timber with aluminium cladding. Both the glazing and the frame were replaced with new windows with higher performance. In this case, new windows are triple-glazed windows with inward opening, have wooden frames and aluminium cladding, and U_{window} value of 1.0 $^{W}/_{m^2}\,K$, which complies with the Swedish National Board of Housing, Building and Planning (Boverket), limitation values for the heat transfer coefficient of windows, U_{window} value of 1.2 $^{W}/_{m^2}\,K$. Moreover, new triple-glazed windows were chosen based on the OneClick LCA EPD database data (One Click LCA). The disposition of existing and new windows on the façade, as well as their area and values, are shown in Table 7.

Table 7. The disposition of existing and new windows on the façade, and their surface area.

Description	Disposition on the facade	Dimensions of windows (m)	Number of windows (pc)	Surface area (m^2)
Existing windows	East	1.3x1.5	24	46.80
		1.2x1.2	2	2.88
	West	1.2x1.5	32	57.60
		1.2x1.2	3	4.32
		1.2x0.8	1	0.96
	North	1.4x1.5	3	6.30
	South	1.4x1.5	6	12.60
Total			70	131.46
New windows	East	1.3x1.5	24	46.80
		1.2x1.2	3	4.32
	West	1.2x1.5	28	50.40
		1.2x1.2	4	5.76
		1.2x0.8	1	0.96
	North	1.4x1.5	2	4.20
	South	1.4x1.5	6	12.60
Total			68	125.04

However, the U_{window} value is not the only consideration when choosing a glazing method. In design choices, for example, double-glazed windows were also taken into consideration; however, U_{window} values for this type of windows ranging from 1.3-2.8 $^{W}/_{m^2}\,K$, which does not comply with legislative regulations. Moreover, triple-glazed windows provide better thermal and sound insulation than double-glazed windows and cause less condensation to occur. On the other hand, triple-glazing windows are heavier than double-glazing, which increases transportation and installation costs. Moreover, both embodied energy and cost are higher for triple glazing, which is understandable since more material is used. Table 8 shows different properties of high-performance double and triple glazing windows (Konstantinou 2014; Pinteric 2021).

Table 8. Different properties of high-performance double and triple glazing windows (Source by Konstantinou (2014) and Pinteric (2021)).

Glazing type (windows)	Weight $(^{kg}/_{m^2})$	Embodied energy $(^{CO_2e}/_{unit})$	Service life of the component $(year)$
Double glazing	20	98.67	40
Triple glazing	43.5	152.0	60

The data in Table 7. reveals that triple-glazed windows have a higher embodied carbon footprint than double-glazed windows. However, the case study accounted for implementing CE strategies and CD approaches. These measures aim to slow and close future cycles for each window component and ensure the proper EOL treatment, which involves recycling and recovery. Notably, the chosen window type has a service life of 60 years, enabling its recovery and reuse in future lifecycles.

Besides replacing existing windows, one of the requirements for building refurbishment of the case study was to add balconies and, consequently, new balcony doors. As a result, six existing windows, four located on the west façade and two located on the north facade, were replaced with balcony doors. This was achieved by enlarging existing window areas by removing the parapets of the previous windows. On the other hand, two balcony doors on the south façade remained in their dimensions, and existing balcony doors were replaced with new ones with better performances. Similarly to windows, new balcony doors are triple-glazed and have outward openings, wooden frames, and aluminium cladding, and $U_{balcony\ door}$ value of 1.2 $^{W}/_{m^2}\,K$, which complies with the Swedish National Board of Housing, Building and Planning (Boverket). Table 9 shows the disposition of new balcony doors on the façade and their surface area, while Table 10 shows properties of the triple glazing balcony door, outward opening, wooden frame with aluminium cladding.

Table 9. The disposition of new balcony doors on the façade and their surface area.

Description	Disposition on the facade	Dimensions of windows (m)	Number of windows (pc)	Surface area (m^2)
Balcony door	West	1.2x2.1	4	10.08
	North	1.2x2.1	2	5.04
		1.8x2.1	1	3.78
	South	1.8x2.1	2	7.56
Total			9	26.46

Table 10. Properties of the triple glazing balcony door, outward opening, wooden frame with aluminium cladding (Source by Helsinki: One Click LCA Ltd. (2015)).

Glazing type (balcony doors)	Weight (kg/m^2)	Embodied energy $(CO_2e/unit)$	Service life of the component $(year)$
Triple glazing	32.4	93.7	60

Moreover, the existing outer doors, one which leads to the basement from the outside, and auxiliary services, such as storage and laundry, and another which leads to the lift, were replaced with new ones with better performance, which complies with the Swedish National Board of Housing, Building and Planning (Boverket) limitations, U_{door} value of 1.2 $W/m^2 K$. In line with the CE principles, replacing the existing outer doors in the case mentioned in the above study complied with the CE strategies. Implementing the new component considered future cycles, including EOL treatment, which ensures that the new component made from virgin materials can be recycled and recovered. Table 11 shows the disposition of doors on the façade and their surface area, while Table 12 shows properties of outer steel doors made from stainless steel.

Table 11. The disposition of outer doors on the façade and their surface area.

Description	Disposition on the facade	Dimensions of doors (m)	Number of doors (pc)	Surface area (m^2)
Outer door	East	1.2x2.1	2	5.04
Total			2	5.04

Table 12. Properties of outer steel doors (Source by Helsinki: One Click LCA Ltd. (2015)).

Glazing type (balcony doors)	Weight (kg/m^2)	Embodied energy $(CO_2e/unit)$	Service life of the component $(year)$
Steel door	32.4	314.00	30

Despite replacing a large portion of the existing windows with newer, more high-performing models, preserving the original entrances by simply replacing the windowpanes with more efficient alternatives was necessary to maintain the architectural integrity of the building. The old glass pane is removed, and the new is fixed on the existing frame, in this case, the wooden frame with aluminium cladding. As the new glazing had a different width than the original, it is usually supported by an additional part nailed on the old frame. The advantage is that the thermal and acoustic performance of the window is economically and quickly improved. Figure 10 shows the example of a double-glazing pane fixed on the existing timber frame (Konstantinou 2014).

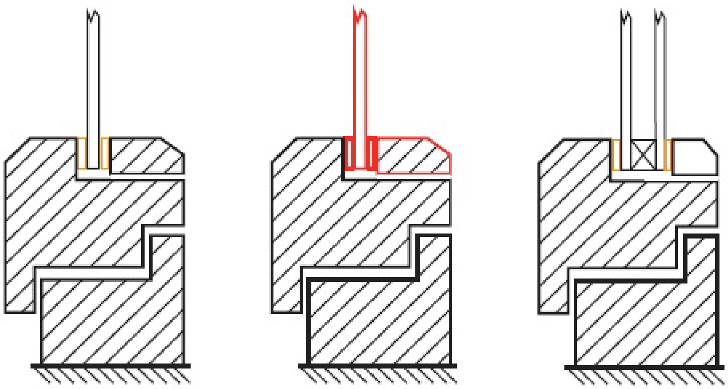


Figure 10. The example of double-glazing pane fixed on the existing timber frame (Source by Konstantinou (2014)).

Like new windows and balcony door, in this way the original entrances have $U_{entrance}$ value of 1.2 $W/_{m^2}$, which complied with the Swedish National Board of Housing, Building and Planning (Boverket). Table 13 shows the disposition of entrances on the façade and surface area.

Table 13. The disposition of original entrances on the façade and their surface area.

Description	Disposition on the facade	Dimensions of doors and windows (m)	Number of doors and windows (pc)	Surface area (m^2)
Entrance	East	2.7x2.2	4	23.76
		2.7x1.2	2	6.48
Total			6	30.24

5.2.3. Balconies

The balcony is a common feature of the building envelope, offering the possibility to create private or semi-private exterior spaces for the dwellings (Konstantinou 2014). In this case, new balconies were added to the existing building structure and its west and north façades. These balconies were treated as separate building elements, suspended on the existing outer wall. This way of attaching the balconies created a thermal break between the new balcony and the existing wall, improving the energy performance of the building. The construction of the new balcony was planned using CD approaches to slow and close material loops. Table 14 shows the disposition of balconies on the façade and their surface area.

Table 14. The disposition of balconies on the façade and their surface area.

Description	Disposition on the facade	Dimensions of balconies (m)	Number of balconies (pc)	Surface area (m^2)
Balcony	West	3.0x1.5	4	18.00
	North	3.0x1.5	2	9.00
Total			6	27.00

5.2.4. Floor construction

The energy retrofitting of the floor construction was necessary, especially in the unoccupied and unheated basement and the new heated attic. The existing floor construction required renovation to improve its energy performance. The heat losses from the occupied space on the floor to the unoccupied space below, such as cellars and basements, were significant, resulting in approximately 20% more energy consumption in apartments. The insulation method and material choice depended on the existing construction and its accessibility. For the existing building, the renovation measure for the floor construction between the unheated basement and apartments on the ground floor, included striping existing floor elements, such as vinyl and fibreboard, and upgrading it with added insulation and new finishing floor elements, such as recovered and reused wood floor decking, with a damp-proof membrane between the insulation and floor finishing. On the other hand, the renovation measure for the floor construction, between the attic and apartments on the first floor, included additional insulation between the existing floor wooden joints. This method allowed for improving the energy performance of the floor construction without compromising the height of the basement or apartments (Konstantinou 2014).

Both renovation measures considered several CD principles. In the case of narrowing loops, the design minimized the use of materials or the use of virgin materials by keeping the existing floor construction and strengthening it where necessary. Further, in the case of slowing material loops, future lifecycles of components were considered, allowing for the standardised use of all materials applied in future lifecycles when needed. Then, in the case of closing material loops with upcycling, all materials could be recovered and reused. In the case of renovation measures, for both types of floors, the variation of insulation type was based on the type of existing construction, materials service life, and ability to be reused in future lifecycles, as well as the ability to comply with CD approaches, in terms of standardisation of components. Therefore, in this case, the insulation considered for floor construction is EPS insulation. Additionally, all added components to the existing construction, such as reinforced concrete for the floor between the basement and the ground floor and loading wood construction for the floor between the attic and the first floor, were considered. The floor construction details, between the unheated basement and the ground floor are shown in Figure 11, while the floor construction between the apartments is shown in Figure 12.

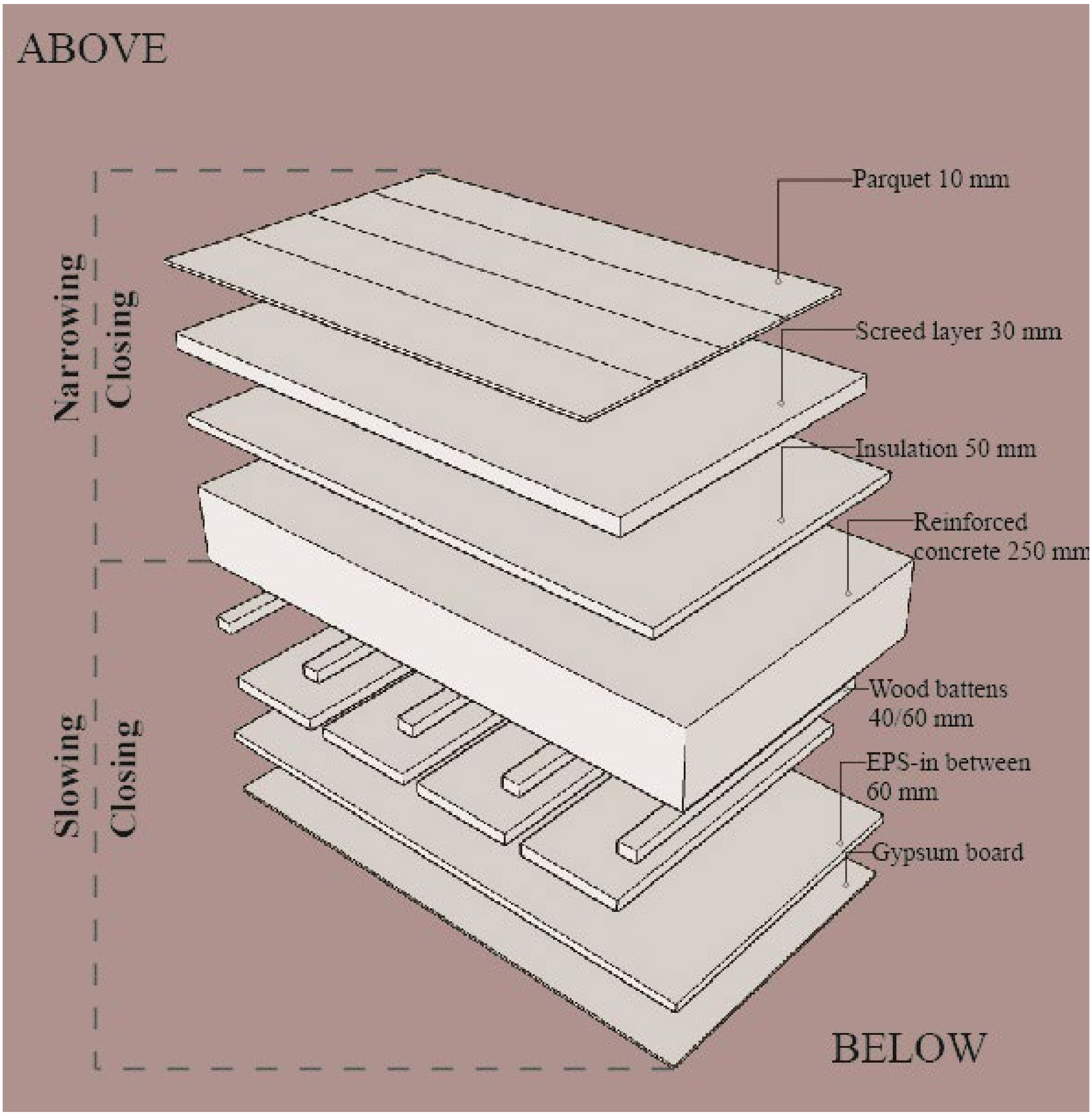


Figure 11. The floor construction between the unheated basement and ground floor.

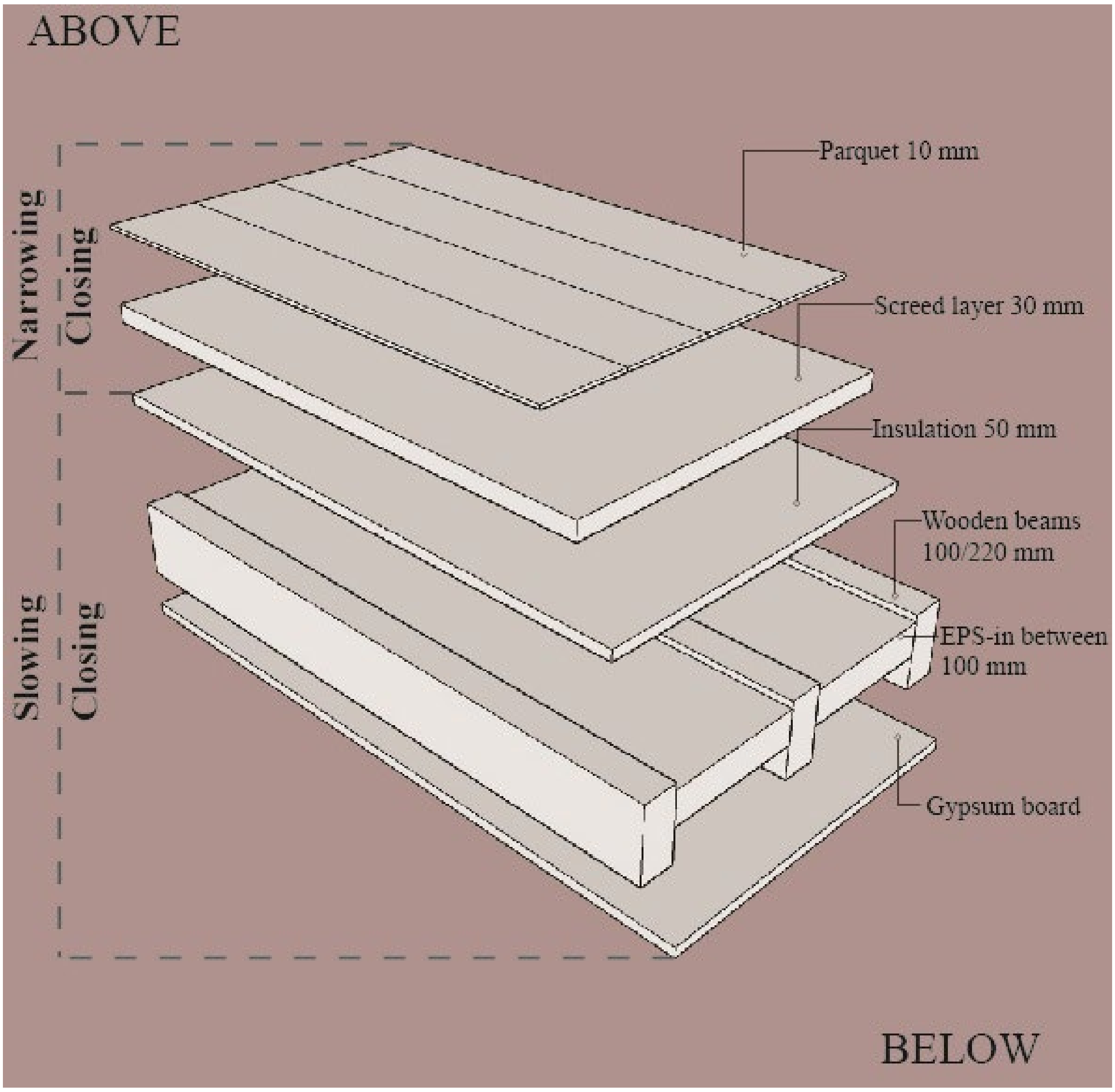


Figure 12. The floor construction between the apartments.

5.2.5. Ventilation System

The existing exhaust and supply ventilation with a heat recovery system (FTX), was replaced by the new exhaust and supply ventilation with a heat recovery system, a better-performing one. In this case, the SFP for the return air ventilation was 1.5 ${kW}/_{(m^3 * s)}$, with the heat exchanger efficiency of 83%. While some studies have indicated the potential to upgrade the current FTX system for improved performance while maintaining the existing ventilation infrastructure, this was not a feasible option in this scenario due to the adoption of a new function for the existing floor plan and various changes.

5.2.6. HD and DHW System

The space heating, as well as the DHW demand, was still covered by the DH system of Gothenburg city.

6. Results

This chapter presents the findings from the methods used in the study. First, it outlines the transmission losses and energy results derived from the calculations and energy report. It then describes the results obtained through the CE LD allocation approach and the life cycle LCA analysis.

6.1. Transmission losses and specific energy use

Transmission losses for the building envelope, for both the existing building and case study, which adopted CE strategies with improved U-values, are shown in Table 15 (see Appendix B: pp.1-2).

Table 15. Transmission losses through the building envelope.

	Building envelope	Area (A) m^2	U-value $(^{W}/_{m^2 * K})$	U*A $(^{W}/_{K})$	Part of total losses %
Existing building envelope	Outer walls	688.20	0.70	481.74	23.24
	Outer walls basement	163.50	0.65	106.27	5.12
	Roof	745.00	1.20	894.00	42.12
	Floor	432.00	0.35	151.20	7.29
	Windows	131.46	2.70	354.94	17.12
	Doors	35.28	2.40	84.67	4.08
	Total	2195.44	1.35	2072.82	
Energy retrofitted building envelope	Outer walls above	668.20	0.16	106.90	21.28
	Outer walls basement	163.50	0.17	27.80	5.53
	Roof	745.00	0.12	89.40	17.79
	Ground floor	432.00	0.20	84.40	16.80
	Windows	151.50	1.00	151.50	30.15
	Doors	35.28	1.20	42.33	8.42
	Total	2195.48	0.32	502.33	

It's important to highlight that in the case of the existing building, the most notable transmission losses of the building envelope occur in the roof construction. However, in the energy-retrofitted case, this is significantly reduced. Despite transmission losses from windows being higher in the CE energy-retrofitted case than in the existing building, the overall losses are almost four times lower in the retrofitted case, while the area of windows has increased.

Figure 13 shows the reduction of the annual specific energy use of the case study, compared to the existing building, by applying energy retrofitting measures (see Appendix C: p.1).

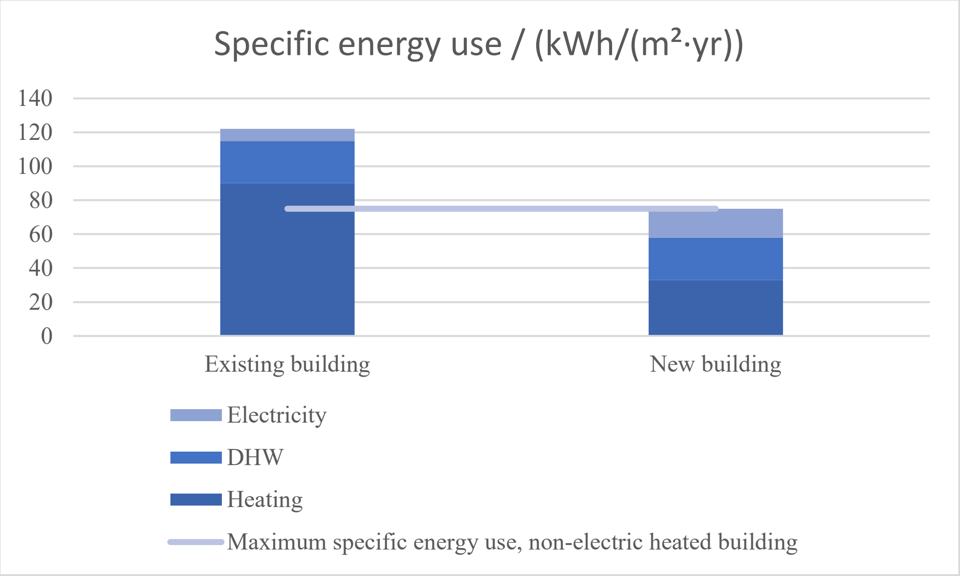


Figure 13. Results of the specific energy use for the case study, before and after energy retrofitting.

The line in Figure 13, represents the maximum allowed specific energy use for the residential building by the building code, and it is 75 $({kWh}/{m^2 * year})$ and that the case study complies with that code. Further, from the results, the property heating demand for the case study was lower than the heating demand for the existing building. On the other hand, the electricity demand for the case study increased compared to that of the existing building, while the demand for DHW remained the same in both cases. The total energy demand reduction for the case study compared to the existing building was 38%. Nevertheless, it is also important to note how energy retrofitting measures affect lowering operational carbon emissions. Figure 14 illustrates that the operational carbon emissions from the existing building after the energy retrofitting lowered by around 38%.

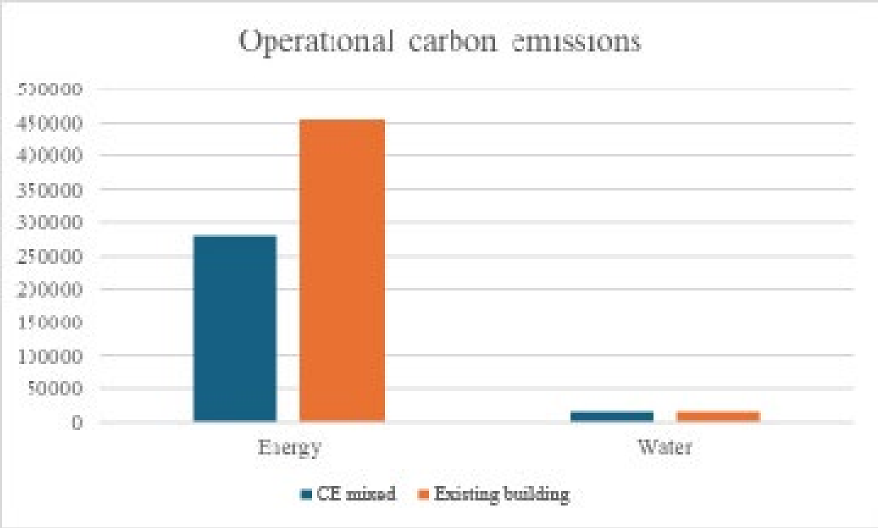


Figure 14. The difference between operational carbon emissions before and after energy retrofitting in the case study.

6.2. CE LD Allocation approach results

The CE LD allocation approach was used to comprehend the environmental impacts of building materials applied in the case study. Further, it was chosen to supplement the LCA analysis to explain CE allocation assumptions of applied materials. To calculate allocation assumptions of applied materials, the allocation factor F=50 was chosen based on the study by Eberhardt et al. (2020). Regarding the number of cycles for materials, the percentage of disposal was based on the One Click LCA database (see Appendix D: p.1).

The CE LD allocation approach analysis examined various building materials applied in the case study, with varying lifecycles. For instance, stainless steel, wood, and EPS insulation components were identified as multi-lifecycle materials. This means they can be reused multiple times before reaching their final disposal stage, lowering their existing and future environmental impact. In contrast, materials like vapour and water membranes, which often require adhesives or other bonding agents during construction, present significant challenges for disassembly and reuse, limiting their lifecycle potential and their existing and future environmental impacts. Table 16 shows the CE LD allocation approach and distribution of environmental impacts for the analysed building components.

Table 16. CE LD allocation approach and distribution of environmental impacts for analysed building components.

Typical building components	A_v	n	V_1	V_2	V_3	V_4	α
Stainless steel anchors	25%	4	49%	33%	17%	1%	16%
Triple glazed windows	50%	2	98%	2%	/	/	96%
EPS	50%	2	98%	2%	/	/	96%
Vapour barrier membrane	100%	1	/	/	/	/	
Gypsum board-finishing layer	50%	2	98%	2%	/	/	96%
Softwood timber frame	33%	3	65%	34%	1%	/	32%
Wooden beams	33%	3	65%	34%	1%	/	32%

The materials show varying numbers of lifecycles and environmental impacts over their respective lifecycles. Figure 15 shows the distribution of environmental impacts across the lifecycles of three selected materials based on the CE LD allocation approach. For instance, in the case of stainless-steel anchors, the number of cycles is four, where the first cycle is to produce virgin material and, in this case, the environmental impact of this material corresponds to 49% of the overall environmental impact. In comparison, the last or fourth cycle corresponds to 1%. In the case of materials with a lower number of cycles, such as the other two examples, softwood timber frame and gypsum board, the first cycle answers correspond to 65% and 98%, while the last cycle corresponds to 1% and 2% of the overall environmental impact, respectively.

The CE LD approach allocates the highest impact share to the first cycle, with progressively lower impact shares in subsequent lifecycles. This approach is a fairer way of dividing burdens because all the cycles share the benefits as well as the responsibility for the environmental impacts (Eberhardt et al. 2020).

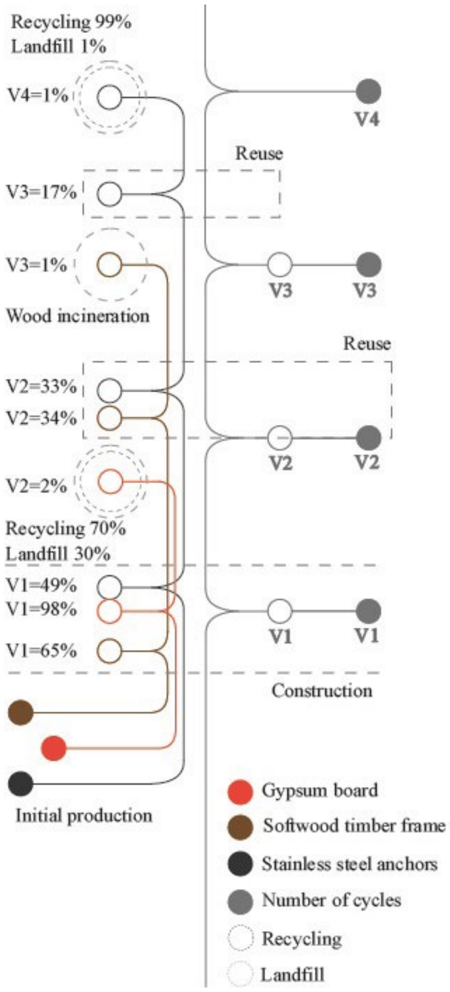


Figure 15. The distribution of environmental impacts across the lifecycles of three selected materials based on the CE LD allocation approach (Source by Beim et al. (2019)).

6.3. LCA results

6.3.1. LCA impacts at building level

Table 17 presents the life cycle environmental impacts per m^2, in the five impact categories for three scenarios: the existing building scenario, the case study and the BAU refurbishment scenario. Notably, from Table 17 it becomes evident that the BAU refurbishment scenario, in terms of GWP ($^{kgCO2eq.}/_{m^2}$) poses the most significant impact compared to the two other scenarios. For instance, the BAU scenario emits 86.100 ($^{kgCO2eq.}/_{m^2}$), whereas the case study emits 70.600 ($^{kgCO2eq.}/_{m^2}$), and the existing building scenario emits 73.100 ($^{kgCO2eq.}/_{m^2}$). Additionally, the case study has a median value of 7.61 ($^{CO2eq.}/_{m^2/year}$), while the environmental impact from the BAU refurbishment scenario has a median value of 9.28 ($^{CO2eq.}/_{m^2/year}$). The case study also has an overall value of 201 ($^{kgCO2eq.}/_{m^2}$) which is in a line with future limit values in 2030, which are 285 ($^{kgCO2eq.}/_{m^2}$) proposed by Boverket (2023).

This difference underscores the urgency of addressing the impact of the BAU scenario. A similar trend is observed in the second category, where the BAU scenario again has the highest impact. However, the existing building scenario leads to the remaining categories. In contrast, the case study demonstrates the potential for the lowest overall impact compared to the other two scenarios. That continues in the case of Module D.

Figure 16 illustrates this analysis further and shows environmental impacts in five analysed categories for three scenarios. The figure shows that the BAU scenario has the highest impact on GWP, while the remaining scenarios have a lower impact. However, it can be noted that the case study does not have a significantly lower GWP impact than the existing building, of just 5%. In contrast, the case study has a significantly lower GWP than the BAU scenario, almost 18%.

Module D, not part of the NollCO2 standard, is crucial for understanding the long-term environmental benefits of building refurbishment practises. While adopting CE strategies and CD approaches may not immediately reduce the embodied carbon emissions from the initial production and construction of materials, these practises can significantly lower the future carbon emissions associated with those materials when reused or repurposed (see Appendix: pp.1-3). For example, building circularity in the case study includes adopting 73.1% of existing materials, while virgin materials are used at 26.9%. Moreover, due to the CE strategies, most virgin and existing materials are returned, with an overall circularity of 76%. This understanding is further reinforced by the data in the table, which shows that the case study poses the lowest environmental impact across all the analysed categories compared to the two other scenarios. It highlights the importance of considering the entire lifecycle of building materials and the ability to reuse those materials to mitigate the environmental consequences for the built environment.

Table 17. The environmental impacts in the five categories for three scenarios (the case study, the BAU scenario, and the existing building scenario).

Life cycle embodied impacts	Design variant	A1-A3	A4	A5	B1-B3	B4-B5	B6	B7	C1-C4	D	Total (excl. D)
Global warming potential (kg CO2-eq./m2)	Case study	1.48E+05	1.76E+04	4.68E+04	1.02E+04	1.08E+05	2.80E+05	1.19E+04	8.32E+04	-3.10E+06	7.06E+05
	BAU scenario	2.49E+05	1.77E+04	1.59E+04	1.04E+04	1.58E+05	2.80E+05	1.19E+04	1.16E+05	-2.96E+06	8.61E+05
	Existing building scenario	/	/	/	2.25E+04	8.17E+04	4.55E+05	1.69E+04	1.02E+05	-2.44E+06	7.31E+05
Acidification potential (kg SO2-eq./m2)	Case study	8.47E+02	4.84E+01	1.16E+02	6.74E+01	7.97E+02	7.33E+02	8.15E+01	3.26E+02	-1.33E+04	3.02E+03
	BAU scenario	1,19E+03	4,90E+01	6,33E+01	6,83E+01	8,11E+02	7.33E+02	9.73E+01	3,54E+02	-1.24E+04	3,37E+03
	Existing building scenario	/	/	/	1.04E+02	4.45E+02	1.44E+03	1.16E+02	3.40E+02	-1.01E+04	2.55E+03
Eutrophication potential (kg PO4-eq./m2)	Case study	6.82E+02	1.03E+01	1.06E+02	6.79E+00	2.14E+02	2.24E+02	1.90E+01	7.08E+01	-2.69E+03	1,33E+03
	BAU scenario	7.77E+02	1.05E+01	9.56E+01	6.97E+00	2.14E+02	2.24E+02	2.26E+01	7.70E+01	-1.86E+03	1.43E+03
	Existing building scenario	/	/	/	3.18E+01	1.11E+02	4.40E+02	2.69E+01	7.99E+01	-1.52E+03	7.14E+02
Ozone depletion potential (kg CFC11-eq./m2)	Case study	1.14E+02	3.17E-03	4.57E+00	8.57E-04	1.02E-02	7.96E-02	8.54E-04	1.38E-02	-9.92E+01	1.19E+02
	BAU scenario	1.41E+02	3.20E-03	5.65E+00	8.93E-04	1.12E-02	7.96E-02	1.02E-03	1.48E-02	-1.60E-01	1.47E+02
	Existing building scenario	/	/	/	1.82E-03	9.61E-03	1.56E-01	1.21E-03	1.51E-02	-1.32E-01	1.93E-01
Total use of primary energy (MJ/m2)	Case study	3.04E+06	3.64E+05	1.15E+06	1.83E+05	2.25E+06	1.34E+07	1.96E+05	2.18E+06	-4.67E+07	2.27E+07
	BAU scenario	5.15E+06	3.67E+05	3.76E+05	1.88E+05	2.25E+06	1.34E+07	2.34E+05	2.05E+06	-4.31E+07	2.40E+07
	Existing building scenario	/	/	/	3.58E+05	1.01E+06	2.63E+07	2.78E+05	2.00E+06	-3.55E+07	3.12E+07

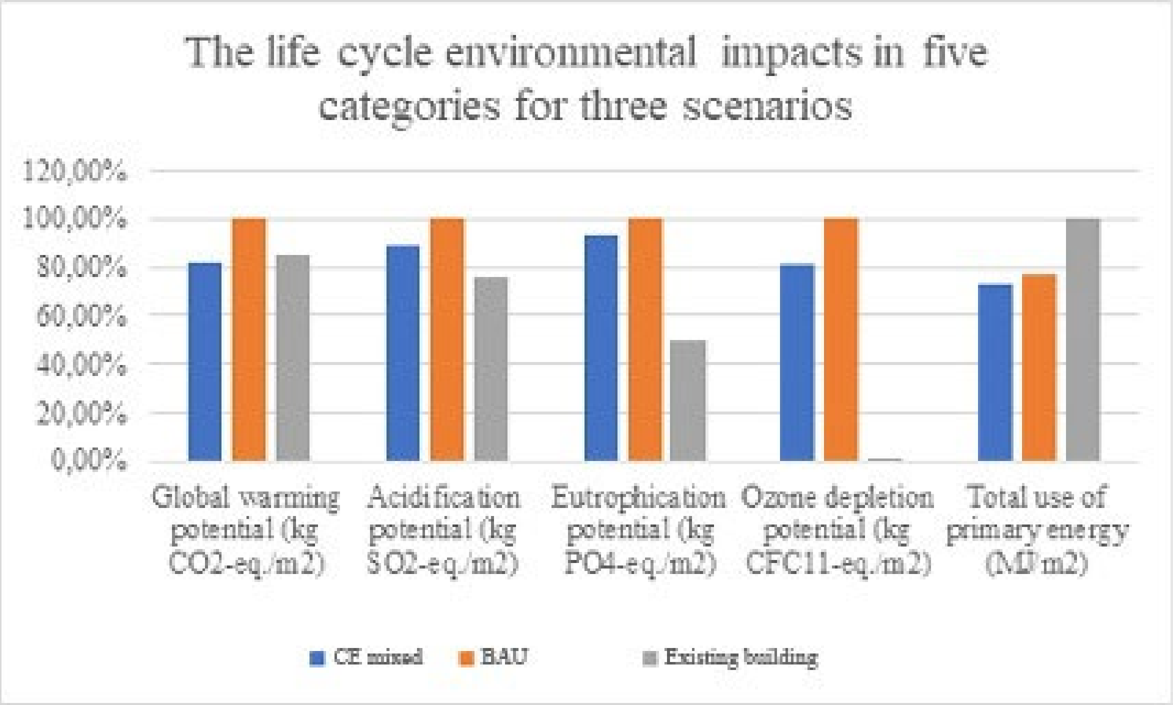


Figure 16. The life cycle environmental impacts in five categories for three scenarios (the case study, the BAU scenario, and the existing building scenario).

Furthermore, the results of the three scenarios are comprehensively analysed in Figure 17. This figure illustrates the combination of A, B and C modules. Notably, in the case of module A, specifically modules $A_1 - A_3$, the BAU refurbishment scenario stands out with the highest impact. In the case of remaining stages of this module, A_4 both the case study and BAU refurbishment scenario have the same impact, while in the module A_5 the case study has higher impact. The existing building scenario was not considered for this module's analysis.

In the case of module B, the existing building scenario has the overall highest impact compared to the other two scenarios. However, this scenario has the lowest impact of all three cases in the module $B_4 - B_5$. Finally, for the module C, the BAU refurbishment scenario has the highest impact, which can be explained by the amount of used materials in the refurbishment and the linear approach towards disposal of these materials. In conclusion, both the case study and the BAU refurbishment scenario reduce GWP from the use stage while increasing GWP from the production stage and construction of material. This analysis also demonstrates the difference in scenarios between impacts that occur today, as in the case of the existing building, and impacts that will occur in the future after the use phase of the building.

Considering all factors, the case study has the lowest environmental impacts due to the lower impact from the initial production and construction stages compared to the standard BAU refurbishment scenario. However, the overall impact of the case study is not much lower than that of the existing building scenario, and it is reduced by 5%. Although the existing building scenario has the highest impact during the building use phase compared to the case study, the production and construction of materials in this scenario almost counteract those results.

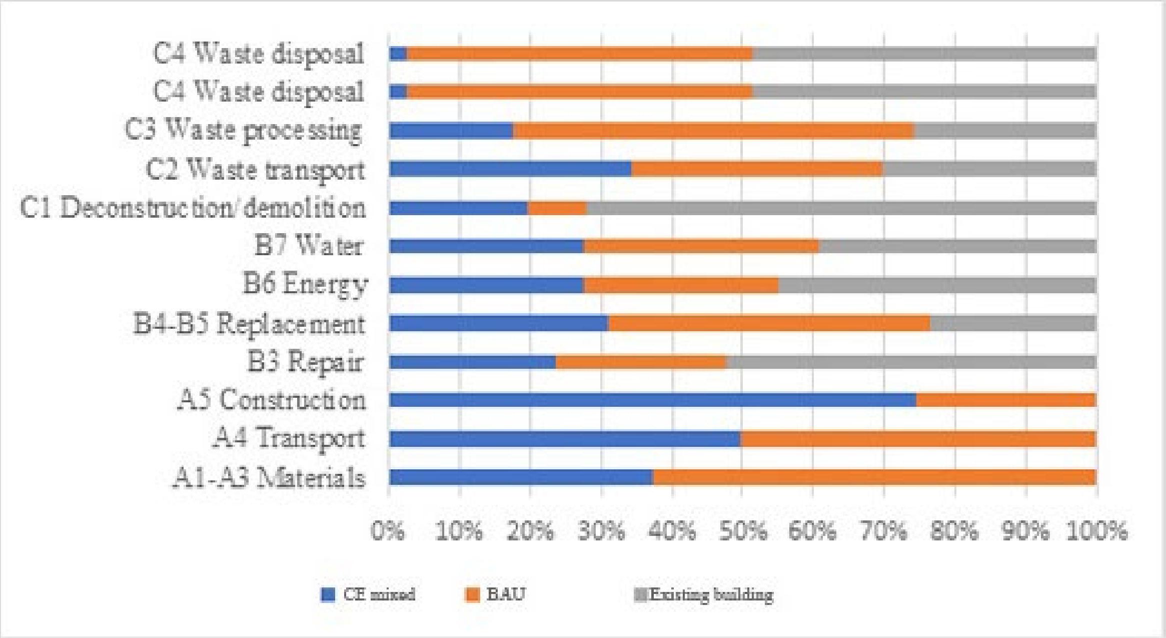


Figure 17. Results for GWP impacts using the LCA analysis modules A, B, and C for three scenarios (the case study, the BAU scenario, and the existing building scenario).

6.3.2. LCA impact at the material level

The BAU refurbishment scenario does not involve using non-virgin materials or CD approaches, while the case study does. Therefore, it was necessary to analyse both scenarios to effectively assess the GWP impact of different building components and materials.

Figure 18 illustrates the difference in the GWP impact of building components and materials in the BAU scenario and the case study. The figure shows that both refurbishment cases have a significant GWP impact. However, the BAU refurbishment scenario has a significantly higher impact, especially in the case of horizontal structures and façade, where almost 37% and 12% of all GWP impact goes to these components. On the other hand, the case study has a higher GWP impact, especially in the case of foundations and substructures, as well as other structures, such as stairs and elevators, with a GWP impact of 16% and 47%, respectively. Further, the slightly higher GWP impact has the case study in the sense of building technology. Thus, more materials were used in the construction so the design could align with CD approaches, and consequently, all applied materials could be reused in the future.

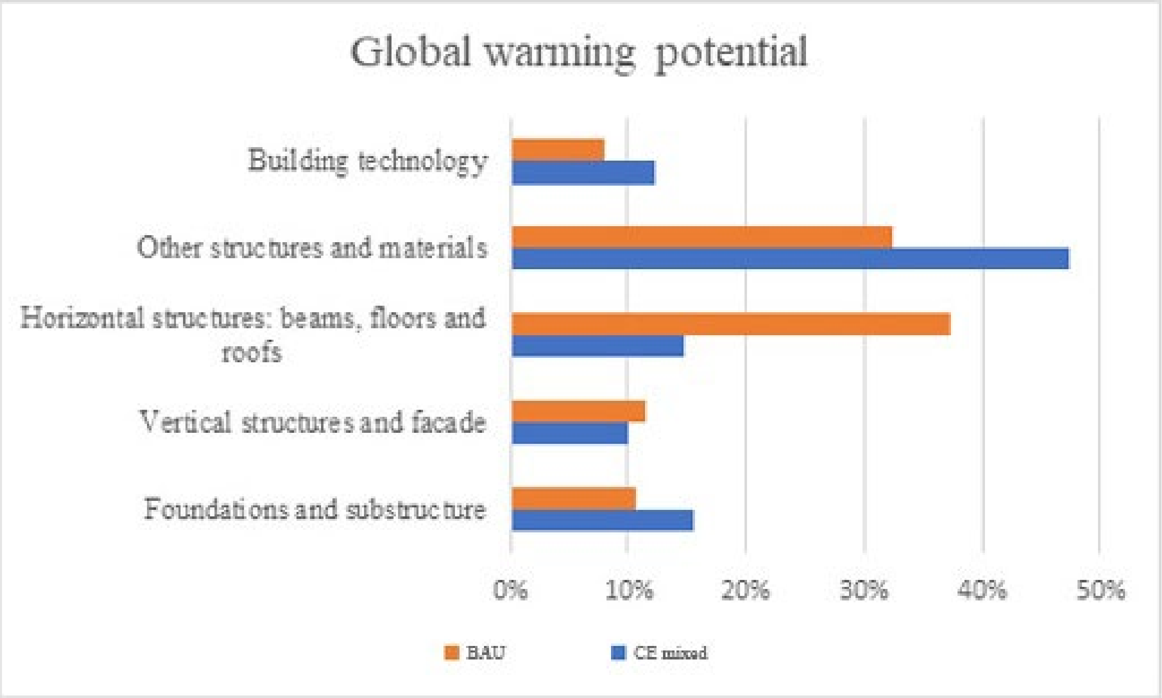


Figure 18. The difference in the GWP impact of building components and materials in the BAU scenario and the case study.

6.3.3. The value of the subsequent material life cycle

The second analysis was necessary to determine the value of reused materials in refurbishment practices, especially in lowering existing and future embodied carbon emissions. This analysis compared two scenarios to the case study: the existing building scenario and the CE reused refurbishment scenario. In this way, the value of reused materials in the next cycle was shown, which can help to promote reusing materials in refurbishment practices. Like the first LCA analysis, the second analysis was based on the life cycle environmental impacts per m^2, in the five impact categories for three cases: the existing building case, the case study and CE reused refurbishment case.

Table 18 shows that the existing building scenario, in terms of GWP ($^{kgCO2eq.}/_{m^2}$) poses the most significant impact compared to the two other scenarios. For instance, the existing building scenario emits 73.100 ($^{kgCO2eq.}/_{m^2}$), whereas the case study emits 70.600 ($^{kgCO2eq.}/_{m^2}$), and the CE reused refurbishment scenario emits 54.900 ($^{kgCO2eq.}/_{m^2}$).

The highest impact in the second category is the case study, whereas the existing building scenario leads in all remaining categories. Further, this analysis shows that the CE reused refurbishment scenario, which accommodates non-virgin materials, shows the lowest overall impact compared to other scenarios. This finding further supports the idea of adopting CE in the built environment, emphasising the importance of using materials with subsequent life cycles while eliminating the high environmental impacts from the initial production stage of materials.

Table 18. The environmental impacts in the five categories for three scenarios (the case study, the CE reused refurbishment scenario, and the existing building scenario).

Life cycle embodied impacts	Design variant	A1-A3	A4	A5	B1-B3	B4-B5	B6	B7	C1-C4	D	Total (excl. D)
Global warming potential (kg CO2-eq./m2)	Case study	1.48E+05	1.76E+04	4.68E+04	1.02E+04	1.08E+05	2.80E+05	1.19E+04	8.32E+04	-3.10E+06	7.06E+05
	CE reused refurbishment scenario	/	1.76E+04	3.86E+04	1.02E+04	1.08E+05	2.80E+05	1.19E+04	8.32E+04	-3.09E+06	5.49E+05
	Existing building scenario	/	/	/	2.25E+04	8.17E+04	4.55E+05	1.69E+04	1.02E+05	-2.44E+06	7.31E+05
Acidification potential (kg SO2-eq./m2)	Case study	8.47E+02	4.84E+01	1.16E+02	6.74E+01	7.97E+02	7.33E+02	8.15E+01	3.26E+02	-1.33E+04	3.02E+03
	CE reused refurbishment scenario	/	4.84E+01	7.75E+01	6.74E+01	7.97E+02	7.33E+02	8.15E+01	3.26E+02	-1.33E+04	2.13E+03
	Existing building scenario	/	/	/	1.04E+02	4.45E+02	1.44E+03	1.16E+02	3.40E+02	-1.01E+04	2.55E+03
Eutrophication potential (kg PO4-eq./m2)	Case study	6.82E+02	1.03E+01	1.06E+02	6.79E+00	2.14E+02	2.24E+02	1.90E+01	7.08E+01	-2.69E+03	1,33E+03
	CE reused refurbishment scenario	/	1.03E+01	1.79E+01	6.79E+00	2.14E+02	2.24E+02	1.90E+01	7.08E+01	-2.61E+03	5.63E+02
	Existing building scenario	/	/	/	3.18E+01	1.11E+02	4.40E+02	2.69E+01	7.99E+01	-1.52E+03	7.14E+02
Ozone depletion potential (kg CFC11-eq./m2)	Case study	1.14E+02	3.17E-03	4.57E+00	8.57E-04	1.02E-02	7.96E-02	8.54E-04	1.38E-02	-9.92E+01	1.19E+02
	CE reused refurbishment scenario	/	3,17E-03	6,11E-03	8,57E-04	1.02E-02	7.96E-02	8.54E-04	1.38E-02	-9.54E+01	1.15E-02
	Existing building scenario	/	/	/	1.82E-03	9.61E-03	1.56E-01	1.21E-03	1.51E-02	-1.32E-01	1.93E-01
Total use of primary energy (MJ/m2)	Case study	3.04E+06	3.64E+05	1.15E+06	1.83E+05	2.25E+06	1.34E+07	1.96E+05	2.18E+06	-4.67E+07	2.27E+07
	CE reused refurbishment scenario	/	3,64E+05	9.49E+06	1.83E+05	2.25E+06	1.34E+07	1.96E+05	2.18E+06	-4.67E+07	1.95E+07
	Existing building scenario	/	/	/	3.58E+05	1.01E+06	2.63E+07	2.78E+05	2.00E+06	-3.55E+07	3.12E+07

Moreover, Figure 19 shows the life cycle environmental impacts in the five categories for the three analysed scenarios. It can be noted that the scenario that used both CE strategies and CD approaches and only non-virgin materials had the lowest impact in all categories. It is also interesting to note that this scenario has an almost 25% and 20% lower GWP impact than the existing building and the case study, respectively.

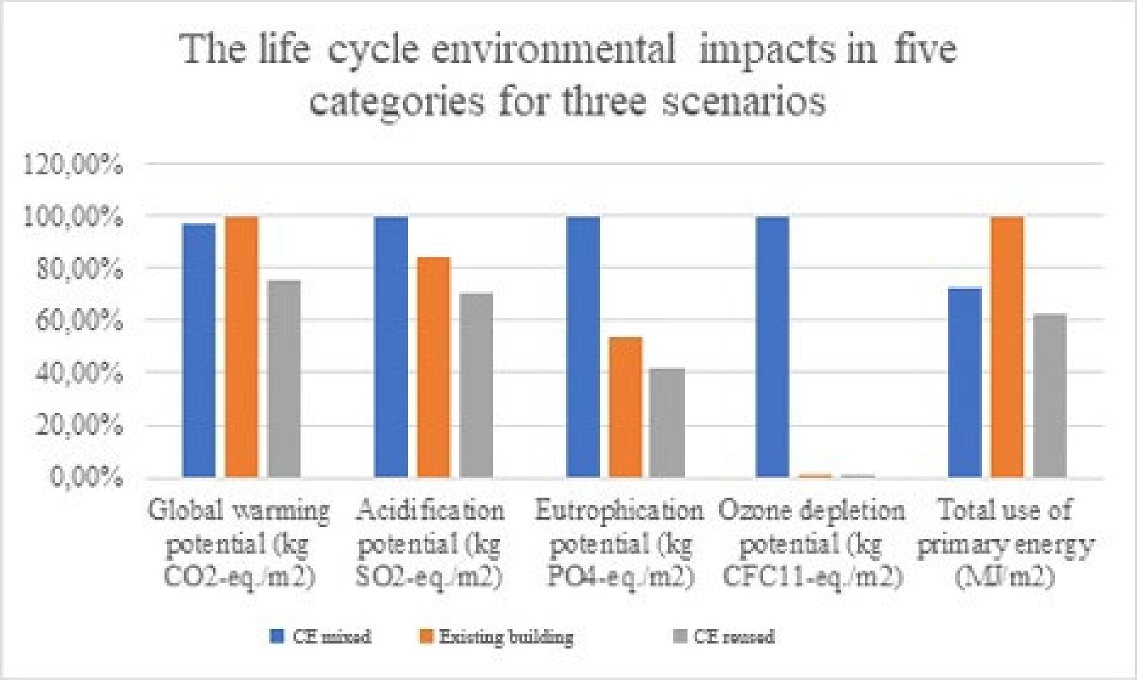


Figure 19. The life cycle environmental impacts in five categories for three scenarios (the case study, the existing building scenario, and the CE reused refurbishment scenario).

Figure 20 shows the results of the three scenarios analysed above. This figure illustrates the combination of A, B and C modules. In the case of module A, modules $A_1 - A_3$, the case study shows the highest impact, and in remaining stages of this module. This was expected, as this is the only scenario that applies virgin materials, while the two other cases were not considered for this module analysis.

In module B, the existing building scenario registers the highest impact compared to the other two scenarios. However, it records the lowest impact of all three scenarios in modules $B_4 - B_5$. In contrast, in the module C, the existing building scenario has the highest impact, which can be explained by the volume of materials used and the lack of EOL treatment of these materials. The case study and the CE reused refurbishment scenario reduce GWP from the use stage. In contrast, the case study increases GWP from the production stage and construction of material compared to the CE reused refurbishment scenario.

After considering all factors, the CE reused refurbishment scenario appears to have the lowest environmental impact. This is a significant conclusion, primarily due to the significantly lower impact from the production stage compared to the case study and the lower impact from the use stage of the building compared to the existing building scenario. These findings show the importance of considering the entire life cycle of building components in environmental impact assessments.

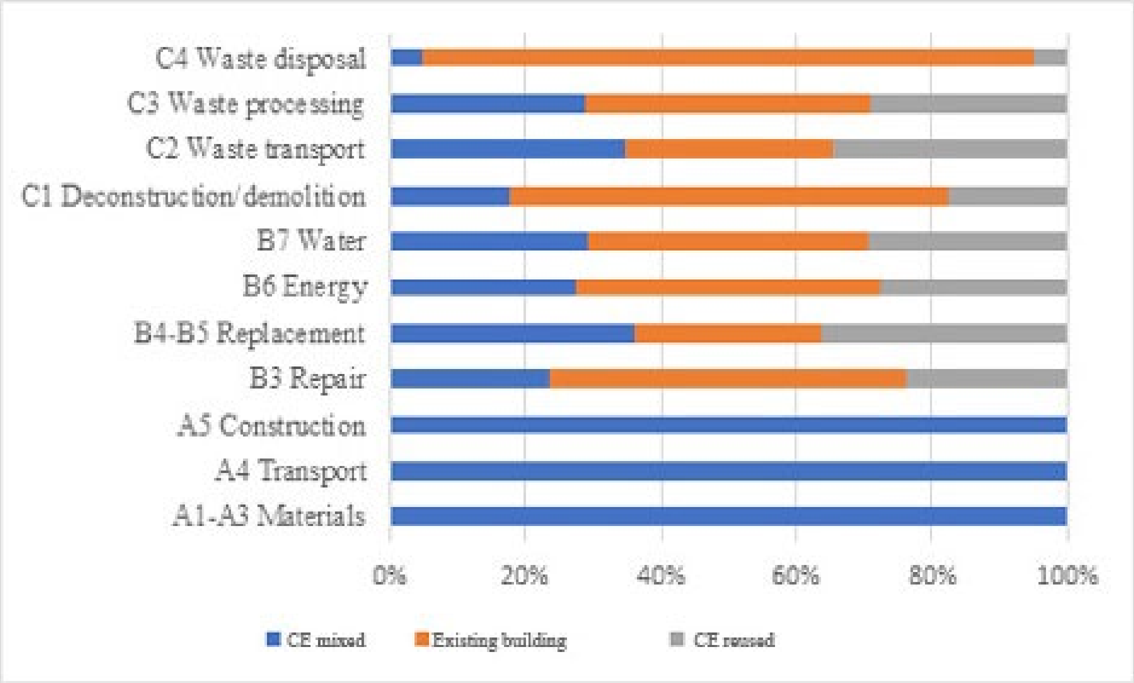


Figure 20. Results for GWP using the LCA analysis modules A, B, and C for three scenarios (the case study, the existing building scenario, and the CE reused refurbishment scenario).

7. Discussion

The study began with an overview of the literature on the topic and a case study analysis in collaboration with the municipal-owned housing company, Familjebostäder. The study aimed to present relevant data; however, it is also necessary to acknowledge certain limitations and potential differences between the existing building project and the case study. Further, the relationship between specific manual calculations and simulation models was not identical. However, the study's objective was not to precisely match the expected results of the existing building project but to demonstrate the ability to apply CE strategies in building refurbishment practises to theoretically lower operational and embodied carbon emissions. Therefore, these potential errors were accepted as the study progressed. The discussion section examines the study results and key indicators influencing the outcome.

7.1. Overview of energy retrofitting measures and results

Significant improvements in the sense of passive and active retrofitting measures were needed in the case study to enhance energy efficiency. For instance, improvements to the building envelope were necessary as passive retrofitting measures. The most significant transmission losses occur through roof construction. On the other hand, in the case study, those happen in windows. Although this can be seen as a disadvantage, it is necessary to mention that the overall surface area of windows increased significantly, followed by the adoption of high-performing windows while improving occupant comfort and reducing overall energy demand.

Further, it is necessary to mention that no measures were considered regarding the foundation of the building, as this building component in the case study was considered an unheated area. However, in the case of any changes to this building component, in the sense of additional insulation, it is relatively complicated and can hardly comply with CE strategies. Additionally, thermal bridges account for 20% of the existing building´s surface area when calculating transmission losses. However, for more accurate calculations, it is necessary to estimate thermal bridges individually, as each building is unique, and these losses can significantly impact the overall transmission losses.

The case study analysis primarily focused on passive measures and their ability to align with CD approaches. However, the objective of the case study was to, besides analysing passive measures, analyse active measures regarding energy retrofitting. In the case of active retrofitting measures, the case study leaned on the company energy report, an analysis of the building's energy usage and potential areas for improvement and adopted report findings. The energy report suggested replacing the existing mechanically balanced ventilation system with a heat recovery (FTX system) with a better-performing one.

Overall, by adopting both passive and active retrofitting measures, the heating demand of the case study was significantly lower than that of the existing building. The demand for DHW remained the same in both cases, while the electricity demand for the case study increased compared to the existing building. However, the overall energy demand was lowered by almost 38%.

7.2. Operational and Embodied carbon emissions

Besides analysing measures that affect operational carbon emissions for the case study, various approaches were considered for lowering embodied carbon emissions from applied materials in building refurbishment. These approaches were based on CE and CD strategies for narrowing, slowing, and closing resource loops. From these strategies, the technical model for the case study was derived. The technical model focused on key components regarding the choice of materials and building construction systems that accommodate future life cycles of applied materials. On the other hand, the case study had its objectives regarding applications of standard materials used in building refurbishment. It meant combining virgin materials with limited non-virgin materials found in the existing building. Therefore, in the case study, all used virgin materials were planned in the construction system, which accommodates their future life cycles and ensures that they can be reused in the future.

The analysis was based on the CE LD allocation approach to determine the future life cycles of applied materials more accurately. This method was also used to comprehend the environmental impacts of virgin materials applied in the case study. For instance, the study revealed that materials like stainless steel, wood, and EPS insulation could be repurposed as multi-lifecycle materials when used in a construction system that accommodates CD approaches while significantly reducing their existing and future embodied environmental impacts. However, materials that require adhesive during construction are unsuitable for multi-life cycle analysis and should be avoided. This analysis was also used to supplement the standard LCA analysis, as it included benefits beyond its boundary only on the theoretical level.

The first LCA analysis of the study case was based on a comparative study of three scenarios: the existing building scenario, the case study that accommodated CE strategies and the BAU refurbishment scenario. By comparing these scenarios, it was possible to determine the operational carbon emissions from the building use phase, the impact of embodied carbon emissions, and the value of CE strategies in building refurbishment.

From this analysis, based on these scenarios, the case study had the overall lowest environmental impact due to the high environmental impact of the operational building phase in the existing building scenario and higher environmental impacts from the initial and production phases of virgin materials used in the BAU refurbishment scenario. However, the case study did not show the expected reduction of total carbon emissions compared to the existing building case, and that reduction was 5%. The explanation for this can be found in that even though it still used a limited amount of non-virgin materials, it still used a significant amount of virgin materials, whose initial production and construction increased carbon emissions. Another explanation for these results can be found in the limitations of the LCA study regarding calculating benefits beyond its boundary and adopting CE principles. It potentially minimises the present value of CE strategies adopted in building refurbishment and reduces environmental impact when reusing applied materials.

Therefore, it was necessary to incorporate another analysis, that compared the case study to the existing building scenario and another scenario based on CE refurbished strategies and using only non-virgin materials. The second analysis showed more expected results, as the CE refurbished scenario based on CE strategies and using only non-virgin materials had the lowest environmental impact compared to other scenarios by 25% and 20%, respectively.

The LCA analysis, which compared the case study to various scenarios, showed the actual values of the CE strategies. Virgin materials can create high environmental impacts when they are first applied. However, these impacts can be reduced and delayed only if these materials are applied and used in the construction system, which incorporates the CE strategies. By doing building refurbishment activities in this way, it is possible to shift focus from present to future activities and create a more comprehensive approach to reducing embodied carbon emissions.

8. Conclusion

With the urgent need for deep renovations in the residential building stock, it becomes necessary to adopt energy retrofitting practises that can effectively reduce operational and embodied carbon emissions. As a result, this study aimed to evaluate the impact of typical deep renovation activities in a case study and assess the effectiveness of implementing CE strategies, with the potential reduction of whole carbon emissions by more than 50%. The quantifying analysis of typical energy retrofitting measures, which adopted CE and CD strategies, shows that it becomes unavoidable not to consider materials' lifecycles and potential reuse abilities, as they cannot be overlooked in building refurbishment practises anymore. However, this approach contrasts with the typical attitude towards deep renovation actions, where using virgin and impactful materials is often justified to achieve targeted energy reduction. Achieving energy reduction is an important goal. It should not be the sole measure of the overall sustainability of building refurbishment projects. To create a sustainable way of energy retrofitting existing building stock, it is essential to consider the lifecycle impacts of applied materials, including their embodied emissions and potential for reuse and recycling in future lifecycles.

The results of this study highlight these findings. For the case study, passive and active retrofitting measures incorporating CE strategies were applied to reduce operational and embodied carbon emissions. Operational carbon emissions were reduced by 38% compared to the existing building, while the overall carbon emissions were reduced by 5%. However, in the case of reducing overall carbon emissions, the result may seem insignificant. Still, it is necessary to note that all applied materials in the case study can be reused as whole or partial building components and materials in future life cycles. Additional LCA analysis was performed to measure the benefits of applied materials in future life cycles. This analysis showed that the potential usage of reused and non-virgin materials can reduce embodied carbon emissions by 20% compared to the existing building.

The study findings show that implementing CE strategies in building refurbishment practises is possible at the building level. However, to achieve this shift from linear to circular economy at the industry level, various stakeholders need to overcome existing barriers, such as social, financial, technical, and regulatory. By overcoming these barriers, it will be possible to create benefits for future life cycles of used materials, incorporate their environmental impact, and go beyond the same cost-benefit methods to quantify the value of these materials. As a result, the present disposal approach towards the economy in the construction industry will move towards maintaining and reusing materials.

Therefore, further research should focus on finding inclusive technical and business modules that will increase deep renovation and the step-by-step renovation of the existing building stock. The existing building stock will then be treated as material banks, which can adopt locally sourced innovative, bio, reused, and recycled materials with multiple life cycles on different scales.

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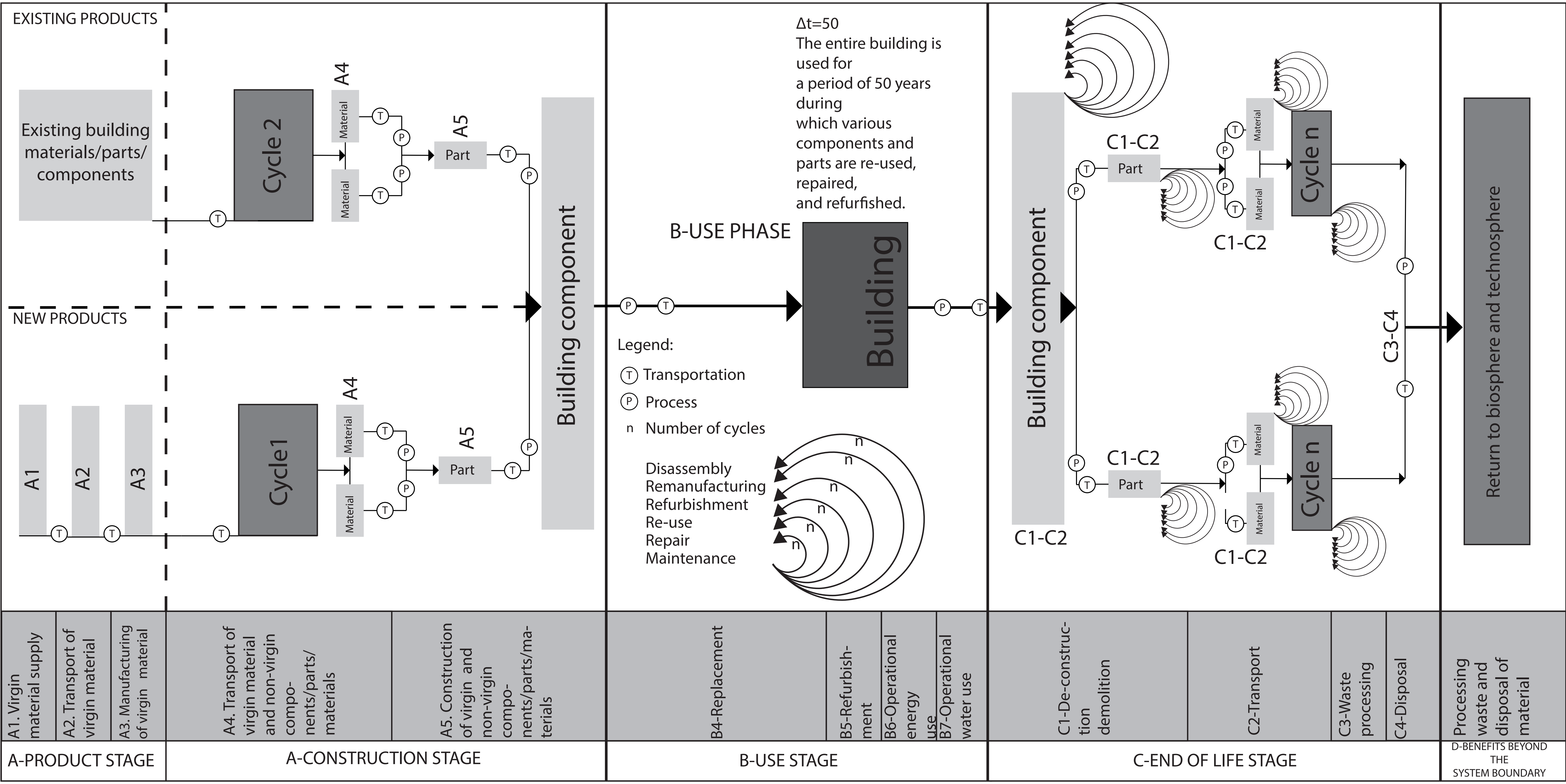
Appendix A

The LCA analysis with CE strategies (Source by Stijn (2023).



Appendix B

Transmission losses through the building envelope components

Building component		Thickness (mm)	Conductivity $(W/m * K)$	Specific heat $(J/kg * K)$
Facade				
Existing construction	Paint	15	0.200	/
	Lime plaster	15	0.730	1050
	Lightweight concrete block	120	0.800	920
	Brick wall	240	0.600	920
New construction	Stainless steel anchors	10	203	940
	Softwood timber frame	160	0.130	2090
	Stainless steel anchors	10	203	940
	EPS-in between timber frame	160	0.038	1260
	Weatherproofing Vapour Barrier Membrane	10	0.120	2090
	Air gap	40	/	/
	Cladding-Wooden facade	10	/	/
Roof				
New construction	Roof tiles	15	0.990	880
	Wood battens	48/24	0.130	2090
	Wood battens with air gap	26/48	0.130	2090
	Plywood	15	0.140	2010
	Weatherproofing Vapour Barrier Membrane	10	0.120	2090
EC	Wooden beams	100/140	0.130	2090
New construction	Wooden beams	100/140	0.130	2090
	EPS-in between wooden beams	140	0.038	1260
	EPS-in between wooden	140	0.038	1260
	Vapour barrier membrane	10	0.26	960
	Gypsum board-finishing layer	12.5	0.021	840
Floor construction above basement				
NC	Parquet	10	0.21	1670
Existing construction	Screed layer	30	1.40	1050
	EPS	50	0.038	1260
	Reinforced concrete	250	1.51	960
New construction	Wooden battens	40/60	0.130	2090
	EPS insulation	60	0.038	1260
	Plywood	15	0.140	2010
	Gypsum board-finishing layer	12.5	0.021	840
Celling (between apartment floors)				
NC	Parquet	10	0.21	1670
Existing construction	Screed layer	30	1.40	1050
	EPS	50	0.038	1260
	Wood beams	220	0.130	2090

New construction	EPS	100	0.038	1260
	Plywood	15	0.140	2010
	Gypsum board-finishing layer	12.5	0.021	840
Basement wall				
Existing construction	Paint	15	0.200	/
	Lime plaster	15	0.730	1050
	Lightweight concrete block	120	0.800	920
	Brick wall	240	0.600	920
	Weatherproofing Vapour Barrier Membrane	10	0.120	2090
New Construction	EPS	180	0.038	1260
	Mesh reinforcement	/	/	/
	Adhesive	/	/	/
	Finishing coating	15	0.700	1050

Appendix C

The annual specific energy use of the case study, before and after renovation.

Existing FTX system	
Ventilation ($^{l}/_{s*m^2}$)	/
Ventilation system	FTX CAV
SFP ($^{kW}/_{(m^3/s)}$)	<2.5
Heating setpoint ($^\circ C$)	21
Heating system	District heating
Specific energy use of the existing building	
Household electricity $\left(^{kWh}/_{m^2}\ per\ year\right)$	7
Domestic hot water (DHW) $\left(^{kWh}/_{m^2}\ per\ year\right)$	25
Heat demand, including system losses $\left(^{kWh}/_{m^2}\ per\ year\right)$	90
Total building energy use $\left(^{kWh}/_{m^2}\ per\ year\right)$	122

New FTX system	
Ventilation ($^{l}/_{s*m^2}$)	0.35
Ventilation system	FTX CAV
SFP ($^{kW}/_{(m^3/s)}$)	<1.5
Heating setpoint ($^\circ C$)	21
Heating system	District heating
Specific energy use of the retrofitted building	
Household electricity $\left(^{kWh}/_{m^2}\ per\ year\right)$	17
Domestic hot water (DHW) $\left(^{kWh}/_{m^2}\ per\ year\right)$	25
Heat demand, including system losses $\left(^{kWh}/_{m^2}\ per\ year\right)$	33
Total building energy use $\left(^{kWh}/_{m^2}\ per\ year\right)$	75

Appendix D

CE LD Allocation approach

Stainless steel anchors with the factor F=50 and number of cycles n=4

$A_v = \frac{100\%}{n} = \frac{100\%}{4} = 25\%$

$V_1 = \frac{F*2*100\%}{n*(F+1)} = \frac{50*2*100\%}{4*(50+1)} = 49\%$ $\quad V_4 = \frac{2*100\%}{n*(F+1)} = \frac{2*100\%}{4*(50+1)} = 1\%$

$\alpha = \frac{V_1 - V_4}{n-1} = \frac{49\% - 1\%}{4-1} = 16\%$ $\quad V_2 = V_1 - \alpha = 49\% - 16\%$=33%

$V_3 = 100\% - V_1 - V_2 - V_4 = 17\%$

Softwood timber frame with the factor F=50 and number of cycles n=3

$A_v = \frac{100\%}{n} = \frac{100\%}{3} = 33\%$

$V_1 = \frac{F*2*100\%}{n*(F+1)} = \frac{50*2*100\%}{3*(50+1)} = 65.35\%$ $\quad V_3 = \frac{2*100\%}{n*(F+1)} = \frac{2*100\%}{3*(50+1)} = 1.30\%$

$\alpha = \frac{V_1 - V_3}{n-1} = \frac{65\% - 1\%}{3-1} = 32.02\%$

$V_2 = V_1 - \alpha = 65.35\% - 32.02\%$=33.35%

Gypsum board with the factor F=50 and number of cycles n=2

$A_v = \frac{100\%}{n} = \frac{100\%}{3} = 50\%$

$V_1 = \frac{F*2*100\%}{n*(F+1)} = \frac{50*2*100\%}{2*(50+1)} = 98.03\%$ $\quad V_2 = \frac{2*100\%}{n*(F+1)} = \frac{2*100\%}{2*(50+1)} = 1.97\%$

$\alpha = \frac{V_1 - V_4}{n-1} = \frac{98.03\% - 1.97\%}{2-1} = 96.06\%$

Appendix E

CE EOL process and amount of lifecycle of applied materials.

Building component	CE EOL process	CE Amount of lifecycles	CE Assumptions
Facade			
Paint	Inert material land filling	Single	-Paint and plastic-based materials are assumed to be disposed of by incineration while the rest of the product is taken to landfill. -100% reuse of steel, wooden, and insulation materials.
Lime plaster	Concrete recycling	Single	
Lightweight concrete block	Reuse as material	Multiple	
Brick wall	Reuse as material	Multiple	
Stainless steel anchors	Reuse as material	Multiple	
Softwood timber frame	Reuse as material	Multiple	
Stainless steel anchors	Reuse as material	Multiple	
EPS-in between timber frame	Reuse as material	Multiple	
Weatherproofing Vapour Barrier Membrane	Plastic-based incineration	Single	
Air gap	/	/	
Cladding-Wooden facade	Reuse as material	Multiple	
Windows and doors			
Triple glazed windows	Reuse as material	Multiple	-100% reuse of windows and doors as whole products.
Wooden frame with aluminium cladding	Reuse as material	Multiple	
Roof			
Roof tiles	Reuse as material	Multiple	-100% reuse of roof tiles, wooden, and insulation materials. -Plastic-based materials are assumed to be disposed of by incineration while the rest of the product is taken to landfill.
Wood battens	Reuse as material	Multiple	
Wood battens with air gap	Reuse as material	Multiple	
Weatherproofing Vapour Barrier Membrane	Plastic-based incineration	Single	
Wooden beams	Reuse as material	Multiple	
Wooden beams	Reuse as material	Multiple	
EPS-in between wooden beams	Reuse as material	Multiple	
EPS-in between wooden	Reuse as material	Multiple	

Vapour barrier membrane	Plastic-based incineration	Single	
Gypsum board-finishing layer	Recycling of gypsum board	Single	
Floor construction above basement			
Parquet	Reuse as material	Multiple	-100% reuse of wooden and insulation materials. -Plastic-based materials are assumed to be disposed of by incineration while the rest of the product is taken to landfill. -Certain concrete materials are crushed to gravel and reused in initial production.
Screed layer	Concrete recycling	Single	
EPS	Plastic-based incineration	Single	
Reinforced concrete	Concrete recycling	Single	
Wooden beams	Reuse as material	Multiple	
EPS insulation	Reuse as material	Multiple	
Plywood	Reuse as material	Multiple	
Gypsum board-finishing layer	Recycling of gypsum board	Single	
Celling (between apartment floors)			
Parquet	Reuse as material	Multiple	-100% reuse of wooden and insulation materials. -Plastic-based materials are assumed to be disposed of by incineration while the rest of the product is taken to landfill.
Screed layer	Concrete recycling	Single	
EPS	Plastic-based incineration	Single	
Wood beams	Reuse as material	Multiple	
EPS	Reuse as material	Multiple	
Plywood	Reuse as material	Multiple	
Gypsum board-finishing layer	Recycling of gypsum board	Single	
Basement wall			
Paint	Inert material landfilling	Single	-Paint and plastic-based materials are assumed to be disposed of by incineration while the rest of the product is taken to landfill.
Lime plaster	Concrete recycling	Single	
Lightweight concrete block	Reuse as material	Multiple	
Brick wall	Reuse as material	Multiple	
Weatherproofing Vapour Barrier Membrane	Plastic-based incineration	Single	
EPS	Reuse as material	Single	

Mesh reinforcement	Plastic-based incineration	Single	
Adhesive	Plastic-based incineration	Single	
Finishing coating	Inert material landfilling	Single	