The evaluation of sufficiency strategies in the building sector using life cycle assessment

Master's thesis in Industrial Ecology

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

The building sector has a monumental impact on the planet's environmental state. Despite ongoing efforts, emissions are growing, partly due to increasing consumption, where resource improvements are consumed by expenditure. Efficiency and renewables through technology and sustainable resources cannot reduce the impact of growing demand without a decrease in overall consumption.

In recent years, sufficiency has been highlighted as a mitigation strategy with great potential to reduce the environmental impact of the built environment. However, there are few clear examples of definite strategies in the building sector. Furthermore, many building sustainability frameworks include a life cycle assessment, but the result is typically presented as total impact per m^2. This makes sufficiency problematic to evaluate, as the main strategies for the building sector are to reduce impact by reducing building and unit size, material demand, and energy consumption. There are currently few examples of sufficiency in LCA, and none are related to the building sector. For sufficiency to be successful in the building sector, the effect of the strategies needs to be quantifiable by LCA, as this is a prevalent method within sustainability and building performance analysis.

This thesis explores how LCA can be applied to estimate the effect of sufficiency strategies within housing. The study implements the idea of Sufficiency LCA, using a sufficiency functional unit along with the conventional functional unit, evaluating possible measurements and the effect of strategies. Furthermore, the influence of functional units is studied by testing various units that could change the perception of the building's impact and provide a more holistic assessment.

The thesis concludes that a comparison to show the impact saved is required to evaluate sufficiency. One option is through an additional functional unit measuring the savings effect (a sufficiency functional unit), which is most effective for sufficiency strategies regarding unit sizes and functions. The second option is comparative analysis with other products, which works better for strategies concerning material use. Furthermore, including area per capita or capita as a functional unit would better present the function and size of a building, along with highlighting crucial sufficiency strategies, such as density and co-living. Moreover, multiple trade-offs can be seen between embodied and operational emissions and between production, maintenance, and end-of-life stages for materials.

Keywords: Sufficiency, LCA, functional unit, architecture, housing, transformation, density

Utvärdering av strategier för tillräcklighet inom byggsektorn genom livscykelanalys

Examensarbete inom masterprogrammet Industriell Ekologi

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Sammanfattning

Byggsektorn har en monumental inverkan på planetens miljötillstånd.Trots pågående ansträngningar växer utsläppen, delvis på grund av ökad konsumtion, där resursförbättringar äts upp av växande förbrukning. Effektivitet och förnybara energikällor genom teknik och hållbara resurser kan inte minska effekten av en växande efterfrågan utan en reducering av den totala konsumtionen.

Under de senaste åren har tillräcklighet lyfts fram som en strategi med stor potential att minska påverkan av den byggda miljön. Det finns dock få tydliga exempel på implicita strategier inom byggsektorn. Dessutom innehåller många klimatcertifieringar för byggnader en livscykelanalys, men resultatet presenteras rutinmässigt som total påverkan per m^2. Detta gör tillräcklighet problematisk att utvärdera, eftersom huvudstrategierna för byggsektorn är att reducera påverkan genom att minska byggnadens och rummens storlek, materialbehovet och energiförbrukningen. Det finns för närvarande få exempel på tillräcklighet i LCA, och inga är relaterade till byggsektorn. För att tillräcklighet ska bli framgångsrikt inom byggsektorn måste effekten av strategierna vara kvantifierbar med LCA, eftersom detta är en utbredd metod inom hållbarhets- och byggprestandaanalys.

Detta examensarbete undersöker hur LCA kan tillämpas för att bedöma effekten av tillräcklighetsstrategier inom bostäder. Studien implementerar idén om Sufficiency LCA, som med hjälp av en tillräcklig funktionell enhet tillsammans med den konventionella funktionella enheten utvärderar möjliga mätningar och effekten av strategier. Vidare studeras effekten av funktionella enheter genom att testa olika enheter som skulle kunna förändra uppfattningen om byggnadens påverkan och ge en mer nyanserad bedömning.

Examensarbetet drar slutsatsen att en jämförelse som visar sparad efterfrågan krävs för att utvärdera tillräcklighet. Ett alternativ är genom en extra funktionell enhet som mäter besparingseffekten (en tillräcklig funktionell enhet), vilket är mest effektivt för tillräcklighetsstrategier avseende enhetsstorlekar och funktioner. Det andra alternativet är en jämförelse med andra produkter, vilket fungerar bättre för strategier som rör materialanvändning. Dessutom skulle införandet av area per invånare eller invånare som en funktionell enhet bättre reflektera byggnadfunktion och storlek, och även tydliggöra avgörande strategier för tillräcklighet, såsom täthet och co-living. Dessutom kan flera kompromisser ses mellan produktionsutsläpp och operativa utsläpp och mellan produktions-, användnings- och återvinningsstadiet för material.

Nyckelord: Tillräcklighet, LCA, funktionell enhet, arkitektur, bostäder, omvandling, täthet

Contents

Preface

This report is the result of a Master´s thesis of 30 ECTS in the Master´s programme of Industrial Ecology. The work has been conducted at the Department of Architecture and Civil Engineering, division of Building Technology, at Chalmers University of Technology, Sweden. The work was carried out from September 2024 to January 2025 with Doctoral Student Toivo Säwén as supervisor and Associate Professor Alexander Hollberg as examiner.

This thesis is a continuation of my architectural thesis *Efficient Renewable Sufficiency - A dense office transformation for resilient affordable housing*, performed within the Master´s programme of Architecture and Planning Beyond Sustainability at Chalmers University of Technology. The design from the previous project has been used as a basis for sufficient architecture, where theory, project study, and conclusions have been brought into this thesis.

I would like to thank Toivo Säwén for enlightening input on the process and the valuable support, knowledge, and rewarding discussions throughout the semester. Moreover, I would like to send my appreciation to Alexander Hollberg for great insights and valuable feedback during the process. Furthermore, I would like to thank my friends, study peers, and educators who have provided support and exchange of knowledge throughout my educational years.

Finally, I would like to thank my family for all the unconditional encouragement and support I always get from home.

Gothenburg January 2025
Lina Eriksson

Abbreviations and definitions

BOA	*Boarea*, Building area for residential use
Boverket	The Swedish National Board of Housing, Building and Planning
BTA	*Bruttoarea*, Building area including external walls
CO_2-eq	Carbon dioxide-equivalents
Efficiency	Reducing the energy and material needed to produce or consume a good or service
Embodied carbon	Emissions associated with the production (extraction, transport and manufacturing) of a good or service
EPD	Environmental product declaration
Functional unit	Measure of system function output or performance used in LCA
GHG	Greenhouse gases
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
MAB	Manual för Analys av Bostäder/Manual for Housing Analysis
Operational carbon	Emissions associated with energy and resources used to operate the building, i.e. heating, hot water, cooling, ventilation, electricity etc.
Renewables	Meeting the consumption demand using renewable, recyclable energy and resources
SER	Sufficiency, efficiency, and renewables
SGBC	Swedish Green Building Council
Sufficiency	Reducing consumption through lifestyle changes, decreasing demand for a good or service

Building life cycle stages

A1-A3	Production
A4-A5	Construction process
B1-B7	Use
C1-C4	End of life
D	Benefits and loads

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1 Introduction

1.1 Background

It has been known for many years that a continuously growing human consumption rate is unsustainable (Meadows et al., 1972). The result is, among other environmental effects, global climate change, which has motivated the creation of the environmental sustainability focus area. Energy efficiency, net-zero carbon, renewable energy and materials, biodegradability, recycling, and circular economy are commonly proposed mitigation approaches today. However, most of these focus on limiting the impact of consumption, not the consumption itself. This is also the focus of efficiency and renewables, two overarching strategies for overturning human climate change commonly used in the construction sector.

Efficiency focuses on improving impact through technology by reducing the energy and material needed to produce a good or service, for example, less fuel consumption per driven km for a vehicle. Renewables (also labelled consistency) focus on meeting the demand with recyclable, renewable resources and energy, lowering the impact from the whole life-cycle of the product or service. Neither requires substantial lifestyle changes or reduced consumption. However, there is a third concept related to efficiency and renewables. Sufficiency focuses on reducing consumption through changing habits to lower the demand for a product or service, such as driving fewer km with a vehicle (M. Fischer et al., 2023; Hedenus et al., 2018). The purpose of each concept is summarised in Figure 1.

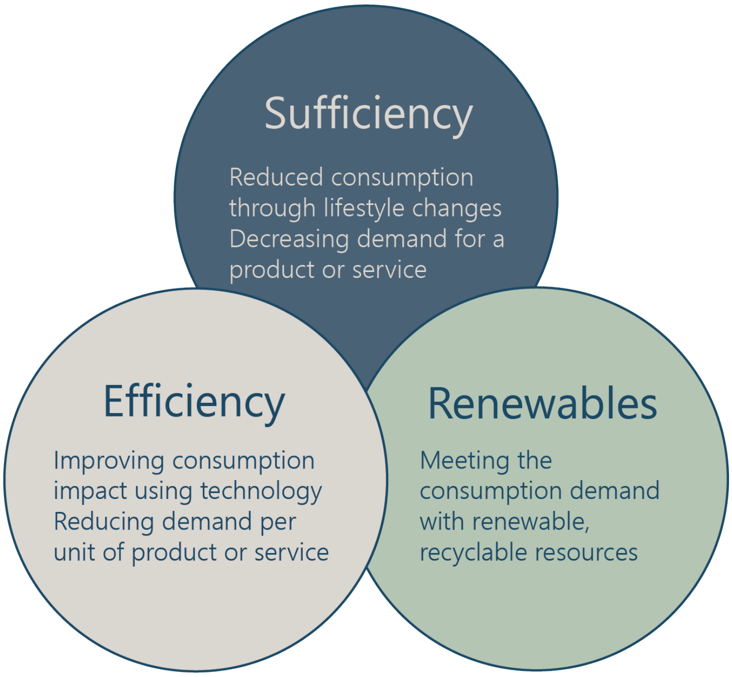


Figure 1: The concepts sufficiency, efficiency, and renewables

Historically, sufficiency has been a less widespread concept within architecture (André, 2024). However, in the Intergovernmental Panel on Climate Change (IPCC) report *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cabeza et al., 2022), sufficiency is highlighted to have great mitigation potential. In the report, a hierarchical framework called SER (sufficiency, efficiency, renewables) is stipulated, and strategies for implementing sufficiency within the built environment are presented. According to the framework, sufficiency should come before efficiency and renewables, although these are also crucial to implement for a holistic building design (Cabeza et al., 2022).

There have been a growing number of publications concerning sufficiency in various sectors in the last 25 years. Since the publication of the IPCC report, sufficiency has gained more traction in the architecture sector (Jungell-Michelsson & Heikkurinen, 2022). However, there are few projects and few clear examples of sufficiency in the built environment, possibly due to the impact on design and the end user. Sufficiency strategies concentrate on lifestyle changes and avoiding consumption, meaning these changes affect the design and the user more clearly. Implementing efficiency and renewables is more straightforward and commonly less influential on design and the end user.

With this background, the author has previously explored the implementation of sufficiency, efficiency, and renewables in architecture through the thesis *Efficient Renewable Sufficiency - A Dense Office Transformation for Resilient Affordable Housing* (Eriksson, 2024). During the project, various design options for transforming offices into housing were tested and evaluated based on design and early-stage daylight, energy, and life cycle assessment (LCA) modelling.

The thesis tested and confirmed the IPCC notion that sufficiency should come first. The LCA results show that the final impact is undoubtedly low, and the step-by-step approach shows savings in each stage. However, tracing the effect of sufficiency measures and what the impact would be without them is a challenge, highlighting the complexity of measuring sufficiency effect. Frameworks and thresholds for sustainable buildings often consider energy use or carbon impact using square meters (m^2) as a functional unit. Examples of frameworks and thresholds commonly used in Sweden are Boverket's building rules (Boverket, 2020) and Miljöbyggnad (Swedish Green Building Council [SGBC], 2022). Since the thresholds are expressed per m^2, the results of building analysis, such as LCA, are often presented per m^2. These measurements do not consider building size, which is a prominent sufficiency measure (Cabeza et al., 2022).

LCA is a widely used methodology for assessing sustainability today, practised in numerous sectors and for various purposes. Most building sustainability frameworks, for example, Miljöbyggnad, BREEAM, and LEED (SGBC, 2022; SGBC and BRE Global, 2023; U.S. Green Building Council, 2023), include LCA to various extent. In addition, efficiency and renewables can offset the energy impact of the building, although they also affect the embodied carbon impact from the construction. LCA measures both the emissions from energy use and the impact of production and construction. Therefore, LCA is a prominent tool for a holistic building analysis and a sustainable built environment. However, there are currently few examples of sufficiency inclusion in LCA, and no case studies have been found in the building sector (André, 2024). According to André (2024), LCA is unable to assess sufficiency measures due to the purpose of reducing functional output. As sufficiency is highlighted as a crucial mitigation concept, the inclusion of sufficiency in LCA is significant for successful implementation for society in general, as well as the building sector.

Hence, the focus of this thesis is on the quantification and measuring of housing sufficiency in life cycle assessment. The project design from the architecture thesis is used as a case study for this thesis. The project builds on the notion that sufficiency should come first, but combining the three concepts is necessary. Strategies and perceptions for architecture are identified through a literature review, and implementations are partly based on the author's previous thesis. The strategies and the consecutive results from the completed project are analysed in detail, providing the basis for this thesis.

1.2 Purpose

The purpose is to evaluate the current LCA methodology regarding sufficiency, using practical examples of sufficiency strategies within buildings. The goal is to quantify the effect of sufficiency strategies using various functional units and reference values and to suggest improvements for the inclusion and visualisation of sufficiency in early-stage design LCA.

1.3 Aim and research questions

This thesis explores the implementation and evaluation of sufficiency, assessing the strategies suggested within the architectural context and the possible trade-offs between embodied and operational carbon. Furthermore, the thesis aims to provide a more holistic view of sustainability within the built environment, deepen the sufficiency discussion with numbers and examples, and provide insights for architects, engineers, and entrepreneurs on how sufficiency strategies can be effectively included and quantified early in the design process.

This is done using the research question

- How can LCA evaluate sufficiency in architecture in a comparable, visual, and holistic way?

With the sub-questions:

- How does the choice of functional unit influence the LCA of sufficiency strategies?
- What are the possible trade-offs between embodied and operational impact when implementing sufficiency in the residential sector?

1.4 Delimitations

Several delimitations are applied to make this project feasible. The three principal target areas of sufficiency in the residential sector are housing, food, and mobility (Akenji et al., 2021). In this thesis, sufficiency and relevant strategies are only considered within housing. Political and planning processes are excluded, as the project focuses more on application for building design. Self-sufficiency is not be considered due to being a means and not an end. The concepts are applied to the chosen building, not society or the housing sector in general.

The work on the previous thesis is a starting point and basis for this work, using the design project and the transformed building as a case study. The strategies from the architectural background are tested in their implementation in the options, meaning that strategies will not be assessed outside the scope of the case study. The building modeling is limited to one typical floor, including slabs and openings, meaning the ground, roof, basement, and entrance floor are excluded from the study. The scope of the life cycle assessment includes all modules for a building LCA (cradle to cradle). However, the study is limited to the impact category total GWP due to feasibility and limited data. Furthermore, the study is geographically limited to Sweden by input values and building location.

The thesis focuses on ecological sustainability, investigating differences in carbon emissions and resource demand. The project does not concentrate on social or economic sustainability.

1.5 Audience

As the thesis aims to provide knowledge about sufficiency and support the implementation in early-stage design, the intended audience for this report is architects, project managers, and contractors involved in the planning and construction of new or existing parts of the built environment. Furthermore, the thesis is also relevant to the method development of LCA and the field of sustainable building design, in addition to policymakers in the broader perspective.

1.6 Report structure

First, an introduction chapter explains the background, purpose, aim, research question, limitations, and audience. Secondly, the theoretical background provides the context of the concepts used, LCA in general and application in sufficiency, LCA in the built environment, and a presentation of the project context. Thirdly, the methodology chapter explains the tools, process, assumptions, and inputs. Next, the results from the various stages are presented. These are further discussed in the consecutive chapter, linking the results to the research questions. The report is summarised in the conclusion, concatenating the results and explicitly answering each question.

2 Theoretical Background

This chapter provides a theoretical foundation for the thesis, helping to understand the notions, methodology choices, and assumptions for the project implementation. First, relevant sustainability knowledge is presented, and the main concepts are explained in general and specifically in the building sector. Next, a brief overview of LCA is provided, with the framework, purpose, and methodology explained. Furthermore, studies of sufficiency in LCA are summarised, followed by an overview of LCA in a building context. Finally, an overview of the case study is given, summarising relevant parts of the thesis project by Eriksson (2024).

2.1 Sufficiency, Efficiency, and Renewables (SER)

Within the sustainable development community, there are three overarching concepts for reducing human environmental impact. Their common aim is reducing demand and the resulting emissions, although they diverge on how.

Sufficiency generally regards consumption reduction through changed habits, resulting in a decreased demand for energy and resources (C. Fischer & Grießhammer, 2013). Changes in lifestyle and behaviour are crucial to reduce the need for a service or good. However, it is not widely adopted and rarely included in official reports. Although heavily debated, it is generally an acknowledged concept considered necessary to overturn climate change (Jungell-Michelsson & Heikkurinen, 2022). Examples of sufficiency measures are lowered indoor temperature, smaller living area, and shorter distance driven (Hedenus et al., 2018).

Efficiency is the most established concept, usually defined as lowering the energy and material needed to produce or consume a good or service. Technology is crucial for improving impact through reducing energy and resource amount per product or service unit. Examples of efficiency are less fuel consumption per km for a vehicle or less kWh use per m^2. Most importantly, efficiency does not require substantial lifestyle changes (Hedenus et al., 2018). Renewables (also known as consistency) is a relatively established concept today. The focus is meeting the demand using renewable, recyclable energy and resources, lowering the whole lifecycle impact of a product or service. Therefore, embodied carbon is crucial, not only the energy and resource consumption in the use and end-of-life phases. Another significant part is recycling: down-cycling into non-reusable states should be avoided (M. Fischer et al., 2023).

All three concepts have the potential to cut both economic and ecological costs. However, they all come with various rebound effects and limits. Sufficiency is often claimed to result in limited growth and thus impact everyday life (Sorrell et al., 2020). Skeptics claim that consumption patterns cannot be controlled, only shifted, and since sufficiency mainly occurs through individual actions, time and money saved might be spent on increased consumption (Hedenus et al., 2018; Sorrell et al., 2020). The limit of sufficiency is human basic needs, although wellbeing is impacted well before that (Spengler, 2016). Efficiency usually comes with increased consumption, for example, longer driving distances for fuel-efficient vehicles, resulting in a large share of savings lost (Hedenus et al., 2018). Efficiency critics also allege that efficiency can only decrease demand, not reach net zero, and therefore not stop climate change alone (Lorek & Spangenberg, 2019). Renewable energy and resource consumption are generally higher as the impact is considered non-existent, although when considering embodied emissions, the overall impact is still increased. Resources are required for the transition towards renewables, and most importantly, renewables cannot be scaled to meet the current green energy demand due to natural constraints (Lorek & Spangenberg, 2019).

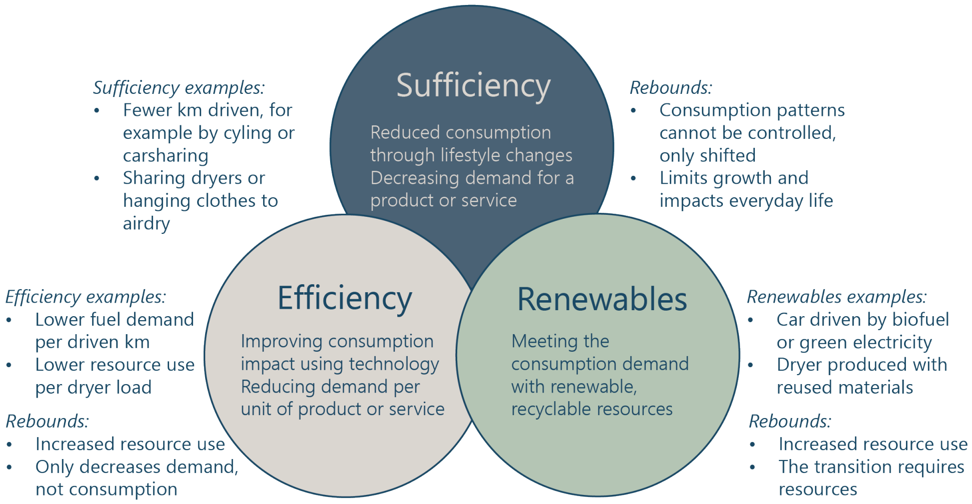


Figure 2: Examples and rebounds for sufficiency, efficiency, and renewables

In summary, the consensus is that all three are needed to reduce climate impact. The strategies are all successful individually, but one alone cannot solve the crisis.

2.2 The SER framework and the building sector

In the report *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, the IPCC introduces sufficiency as a crucial mitigation strategy for reducing climate impact from buildings. The report defines sufficiency policies as *"a set of measures and daily practices that avoid the demand for energy, materials, land, and water while delivering human well-being for all within planetary boundaries"* (Cabeza et al., 2022, p. 31).

According to the IPCC, the implementation of sufficiency in the building sector should follow the SER (sufficiency, efficiency, and renewables) framework, presented in Figure 3. The hierarchical framework states that sufficiency should come first, followed by efficiency and renewables, to reduce the construction and use cost of buildings without reducing user well-being. In the building sector, just like generally, efficiency and renewables are prevailing concepts, while sufficiency is less common and explored (Cabeza et al., 2022).

The aim of sufficiency in the building sector is to avoid material and energy demand during building and material lifecycles, thereby dealing with the causes of human environmental impact. Sufficiency focuses on long-term actions driven by non-technological solutions. The most significant sufficiency driver listed by the IPCC is floor area per capita. Examples of sufficiency strategies mentioned in the report are density, compacity, bioclimatic design, multi-functionality of space, flexibility in size, low maintenance (sustainable) materials, building thermal mass, co-housing, and adaptive reuse of buildings and materials (Cabeza et al., 2022).

The concept of efficiency aims to reduce energy and material intensity and thereby deal with the symptoms of human consumption and the resulting impact. Efficiency focuses on short-term actions from technological solutions. The most significant efficiency driver in the building context is the final energy per floor area. Examples of efficiency strategies are HVAC systems (preferably with heat recovery), smart systems (ventilation, lighting, etc.), appliances, lighting, and water heating (Cabeza et al., 2022).

The concept of renewables aims to reduce the carbon intensity of energy and materials, thereby dealing with the consequential impact of human consumption. Furthermore, renewable measures strengthen resilience to future climate change impacts. The main driver is emissions of greenhouse gases (GHG) per final energy. Strategy examples include renewable energy, batteries, low-carbon materials, recycling, and circular design (Cabeza et al., 2022).

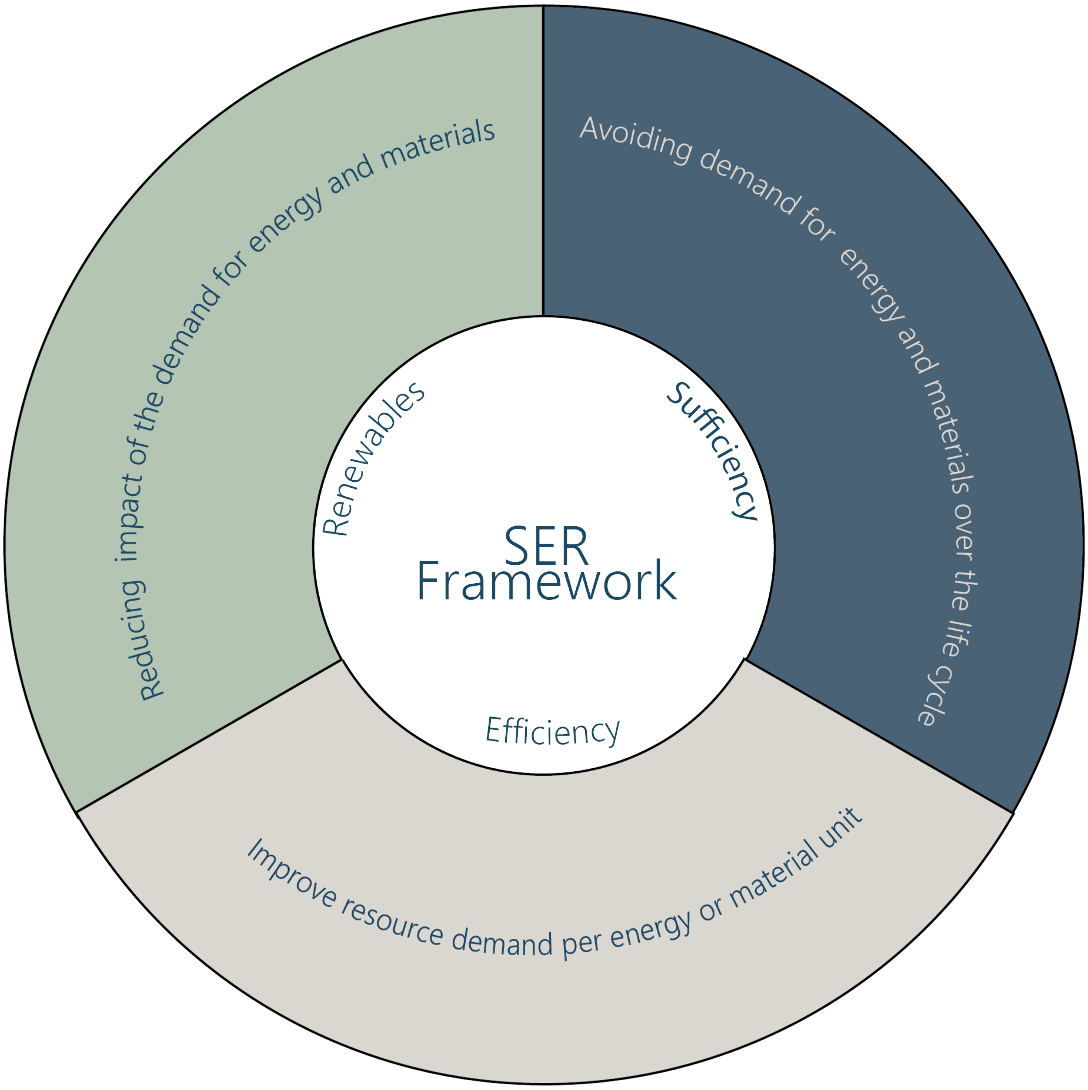


Figure 3: SER framework applied to the building sector, adapted from Cabeza et al. (2022)

According to the IPCC report, the largest sources of high building emissions are population growth, increase in floor area per capita, the inefficiency of the newly constructed buildings, the increase in use, number, and size of appliances, and use of carbon-intensive energy sources (Cabeza et al., 2022). Efficiency has historically been effective in reducing environmental impact, although the savings are often decreased by, and frequently even matched by, an increase in floor area per person. Therefore, sufficiency is needed to reduce the floor area first, followed by efficiency to decrease the required energy and resources and renewables to meet the remaining demand (Bierwirth & Thomas, 2015; Lorek & Spangenberg, 2019).

The report states as a key point that all three concepts are required to mitigate climate impact, with sufficiency to *"align building design, size and use with SDGs"*, efficiency to *"ensure high penetration of best available technologies"* and renewables to *"supplying the remaining energy needs with renewable energy sources"* (Cabeza et al., 2022, p. 103).

The strategies related to the concepts in the building sector are compiled in Figure 4.

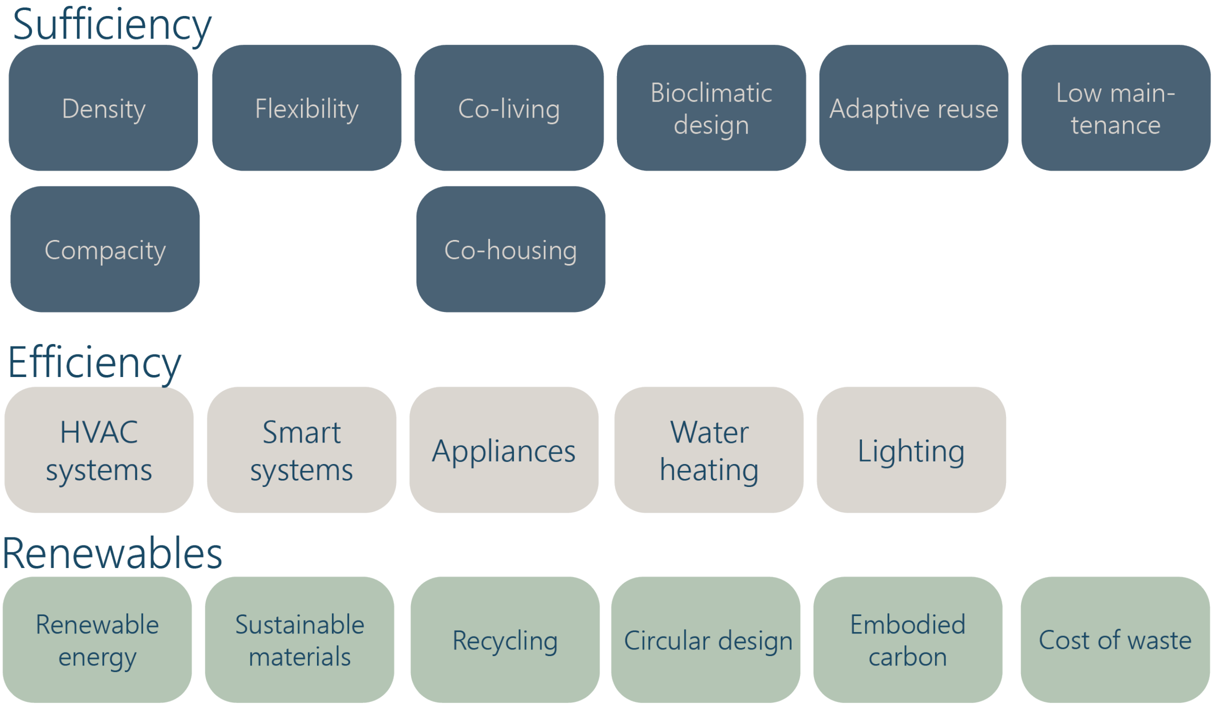


Figure 4: Strategies connected to sufficiency, efficiency and renewables, adapted from Eriksson (2024)

2.3 Sufficiency strategies

Density

Density is generally defined in the building sector as the number of units or residents per unit of land, for example, ha or acre (Mousavinia et al., 2019). Within a housing project, density is often defined as the residential area or number of residents per total project area, also called Floor-Area-Ratio (FAR) (Tröger, 2014). In the architecture thesis (Eriksson, 2024), density has been interpreted as the size of each unit, a simplification due to working within the confinement of a transformation project. This is also the definition in the qualitative housing design framework *Manual för Analys av Bostäder* (MAB) (Granath & Nylander, 2023), used to compare design quality. In MAB, density is measured using dwelling size.

Density can be improved by decreasing the unit size or the number of rooms. Important to note is that a reduced unit or space size affects accessibility, as concluded by Eriksson (2024). Furthermore, density can affect the functionality and design quality. While working with the Swedish standard, balancing space efficiency and functionality is challenging. Finally, crucial to note is that density is affected by the user. The architect can design a dense apartment with appropriate room and function sizes but can not ensure that the number of inhabitants matches the number of intended residents.

Compacity

Compacity refers to the relation between the thermal envelope and floor area. Multiple suggested measurements exist, such as form factor, volume per floor area, and volume per envelope area. Compacity impacts the energy demand of the building through transmission losses from the exposed area. Ways to improve compacity are increased number of floors and lower space height (Barrutieta et al., 2023).

Co-living

Co-living is defined as *"the practice of living with other people in a group of homes that include some shared facilities"* (Cambridge University, n.d.-b), meaning that facilities are shared within the units. Co-living is useful for reducing the size of each unit by sharing required functions, such as kitchens and living rooms, which is beneficial for economic and ecological reasons. Furthermore, the total embodied impact from high-impact functions such as kitchens and bathrooms is decreased if the functions are shared.

Multifunctionality - co-housing

Co-housing is defined as *"a group of homes that include some shared facilities"* (Cambridge University, n.d.-a). Hence, the difference between co-living and co-housing is that co-living means sharing facilities within the home, while co-housing means the sharing of facilities between homes. In the IPCC report, co-housing is labelled multifunctionality through shared spaces (Cabeza et al., 2022). Examples of co-housing are shared laundry and hobby rooms.

Flexibility

Flexibility in architecture refers to the possibility of adapting spaces within the existing premise, for example through movable or removable walls or changeable furniture. Flexibility includes changing the room configuration, the number of rooms, and the room size (Braide, 2019). In MAB, a flexible dwelling is a unit that enables functional removal of the living room, spacious rooms with multiple possible functions (general rooms) and connections, variable number of rooms, and rooms for possible renting (autonomous rooms) (Granath & Nylander, 2023). The benefits of flexible units in housing are the inclusion of various user groups, creating design resilience by preparing for future needs, increasing resident satisfaction, and reducing the need for extensive renovation in the future (Braide, 2019; Granath & Nylander, 2023).

However, there are also challenges with flexibility regarding sufficiency and design. Braide (2019) highlights the difficulty of functionality and flexibility within a dense space, which is also concluded by Eriksson (2024), identifying a clash between density and flexibility in size as adaptability requires extra space. Furthermore, there is a clash with the application of the Swedish Standard, as a specified number of functions and sizes limits the flexibility. With an altered number of residents, function requirements change, impacting design sufficiency.

Bioclimatic design

Bioclimatic design and architecture refer to buildings that interact with the external surrounding environments, using the natural conditions on-site. A bioclimatic design saves energy and creates comfort by adapting to solar and wind conditions through passive heating and cooling. This includes optimisation of glazing and solar gains, natural ventilation, use of nature-based materials, smart materials, and cooling systems with evaporation and radiation (Dounis & Caraiscos, 2009; Manzano-Agugliaro et al., 2015). Important to note is that the distinction of bioclimatic design as a sufficiency strategy can be discussed, as part of the goal is to minimise energy demand and consumption. Hence, passive and bioclimatic design can be categorised as both sufficiency and efficiency.

Adaptive reuse

Adaptive reuse refers to the reuse of a building by giving it a new function, different from the original purpose (Vafaie et al., 2023; van Laar et al., 2024). This provides a building with new life, separate from the practices of refurbishment, renovation, and restoration, where the focus is on extending the life of the existing function (van Laar et al., 2024). Adaptive reuse includes extensive changes to the building by reusing or recycling components for a new purpose, extending the life of old, unused, or derelict buildings (Vafaie et al., 2023; van Laar et al., 2024). Adaptive reuse has gained traction in recent years. For instance, Boverket released a report on adaptive reuse from locales to housing (Boverket, 2021). It has also become more relevant with the many empty offices after the pandemic. The benefits of adaptive reuse are multiple, such as preserving embodied carbon, reducing further operational carbon need, preventing demolition and consequential construction waste and natural resource demand, and social and economic benefits (Mohamed & Marzouk, 2025).

However, there are difficulties with adaptive reuse, especially with turning locales into housing. As concluded by Eriksson (2024) (supported by Boverket (2021)), adaptive reuse is restricting for design. Furthermore, there are challenges regarding economy and implementation, such as uncertainty regarding the construction state, limitations from the structure, costly changes, loss of income, and tax changes (Eriksson, 2024).

Low maintenance

In architecture, maintenance refers to actions that preserve or restore the construction, function, use, or appearance of a building (Boverket, 2023b). Low-maintenance architecture refers to materials or spaces that require fewer and smaller actions to maintain the style over the life cycle of the material or building parts.

2.4 Life Cycle Assessment (LCA)

According to the LCA standard *ISO 14040:2006*, first released by ISO (International Organization for Standardization) in 1997, LCA is defined as *"a technique for assessing the environmental aspects and potential impacts associated with with a product by:*

- *compiling an inventory of relevant inputs and outputs of a product system;*
- *evaluating the potential environmental impacts associated with those inputs and outputs*
- *interpreting results of the inventory; analysis and impact assessment phases in relation to the objectives of the study."* (Baumann & Tillman, 2004, p. 22).

LCA describes the environmental aspects throughout the product's lifecycle, from raw material acquisition to final disposal. LCA has many possible applications, including identification of improvement possibilities throughout the lifecycle, support for design and development, support for decision makers, understanding and characterizing product systems, eco-labelling, and benchmarking (Baumann & Tillman, 2004).

The LCA methodology consists of four stages. The steps are listed in succession here, although it is important to know that LCA is an iterative method, and the steps are not always performed in this order. The first step is to determine the goal and scope, aiming to define the context. This includes goal formulation, with a declaration of why the study is performed and the intended application, along with a proclamation of the intended audience and question to be answered (the purpose). Furthermore, the product or system assessed should be decided, stating the scope. The scope includes the modeling aspects, consisting of a functional unit, system boundaries, an initial flow chart, the impacts studied, and the requirements for the data to be collected and used. Finally, the goal and scope section should include the procedural aspects. Here, the actors are presented, along with reporting and review aspects, since a critical review is mandatory for publishing according to the ISO standard (Baumann & Tillman, 2004).

Secondly, in the inventory analysis, the system is defined according to the goal and scope definition. Here, the complete flow model is created and presented, the data collection for all the activities takes place, including input and outputs for all activities, and finally, resource use data is normalised according to the functional unit (Baumann & Tillman, 2004).

In the impact assessment, the impact of the resource use and emissions in the inventory analysis are quantified. This is done using classification, characterisation, and weighting. Classification refers to sorting inventory results by impact type. Characterisation refers to the calculation of the relative emission contributions through impact categories. An impact category transforms all emissions from a product into one unit. For example, several emission loads contribute to climate change, such as carbon dioxide, methane, or nitrous oxides. A characterisation enables the expression of all emissions in the general GHG emission unit kg CO_2-eq, sorting all GHGs into one global warming impact. Weighting is optional and refers to the comparison of impacts against one another to enable comparison and further aggregate the results. Finally, in the interpretation stage, the results are presented and evaluated. In this chapter, conclusions and recommendations are made (Baumann & Tillman, 2004).

There are two main types of LCA, attributional and consequential, with alternate evaluation focuses and slightly different methodologies. A distinct separation of the two types can be a bit difficult. According to IVL Svenska Miljöinstitutet, they can be considered two complementary ways to view the product system (Erlandsson et al., 2014). Furthermore, IVL states that an attributional LCA only includes direct effects within the life-cycle of the studied product, and the focus is on the calculation of emission loads for the single product. Attributional LCA is characterized by the ambition of being able to calculate and sum up the environmental footprint for all products in the world, and the sum should be equal to the global emissions. A consequential LCA includes an in-direct effect on related products and is suitable for describing the consequences a change within the system can have on the system loads and societal emissions in general (Erlandsson et al., 2014).

2.5 Sufficiency in LCA

Sufficiency measures are not commonly assessed using LCA, with only two studies currently to be found (André, 2024). The first, made by Brändström and Saidani (2022), applies circular measures to a lawn mower study. The assessment includes five different scenarios; a *Linear* material use with no circularity, *Recycling* with closed material loops, *Quality* with longer material use (slowing loops), *Sharing* with fewer products, components and materials (narrowing loops) and *Combined*, bringing the three circular scenarios together. Furthermore, the sufficiency strategy of reduced lawn size and lower cutting frequency was tested for all scenarios, in this case using two different functional units (Brändström & Saidani, 2022).

The second study looks into waste prevention in clothing and furniture in Switzerland. Six scenarios are analysed regarding a change in new clothing consumption, diffusion factor(share of the population engaging in WPA), substitutability (the degree of replacement for a new product), effects on use-phase impacts, and rebound effects. The scenarios are *BAU* (Business as Usual), *SHARE*, *REPAIR*, *REUSE*, *REFUSE*, and *SUFFICIENCY*. The conclusion is that the four assessment factors successfully evaluated the strategies and discovered primary areas for development (Wiprächtiger et al., 2022).

André discusses possible reasons for the lack of sufficiency included in LCA. One theory is that sufficiency's purpose is to reduce consumption, while the purpose of LCA is to compare the same functionality. Another is that sufficiency is not broadly incorporated into society. A third suggestion, supported by Jungell-Michelsson and Heikkurinen (2022), is that sufficiency measures often focus on users on the demand side, while LCA focuses on products on the supply side. The conclusion is that LCA presently appears inadequate for assessing the environmental impact of sufficiency strategies. André argues that LCA evaluating sufficiency will be necessary for the transition toward ecological sustainability. Currently, LCA can only assess efficiency, which, as previously mentioned, is essential but insufficient alone. Sufficiency strategies are necessary, and as LCA is an influential tool for supporting decision-making, developing LCA to evaluate sufficiency is crucial (Cabeza et al., 2022; Lorek & Spangenberg, 2019). Therefore, André creates the expression Sufficiency LCA, aiming to start a debate around sufficiency in LCA and how to include sufficiency measures (André, 2024).

André uses three studies to define the criteria for Sufficiency LCA - Brändström and Saidani (2022), Wiprächtiger et al. (2022), and a third study, an ongoing research project on sufficiency measures at mountain stations. The assessment focuses on how functional output and environmental impact vary with the sufficiency measures used in the studies. The functional unit is divided into what, how much, how long, and how well.

In the lawn study, the size is reduced by 87.5 %, and the frequency is reduced by 50%, while time remains unchanged (Brändström & Saidani, 2022). In the sufficiency option for the clothing study (Wiprächtiger et al., 2022), highlighted by André, the target audience reduces clothing consumption by 50%. The time factor remains unchanged. In the ongoing mountain station study, less fresh food is suggested, resulting in fewer helicopter transports, while the amount of food and the period are the same. In the studies by Brändström and Saidani (2022) and Wiprächtiger et al. (2022), how well the sufficiency measures fulfil the need is not assessed, while the mountain study mentions a change in guest satisfaction (André, 2024).

The conclusion based on these studies is that the what component (the product) needs to be equal between alternatives compared in sufficiency LCA, but that how much (the amount), how long (the time), and how well (the user satisfaction) can diverge. André (2024) highlights the importance of alternatives with similar but different functional outputs, alternatives to be accepted by users and hence considered functionally equivalent. Using the reduced functional output provided by the sufficiency measure would cause, all other things equal, an increase in impact per functional unit. Therefore, André proposes a comparison functional unit, representing the reduced functional output and the output from the equivalent service or product without the sufficiency measure. This would enable visibility of the output reduction, a significant part of sufficiency, as a separate result. The result empowers Sufficiency LCA to quantify the functional non-equivalence overlooked by conventional LCA, facilitating a comparison of both environmental impact and functional output (André, 2024).

2.6 LCA in the built environment

Life Cycle Assessment in the built environment follows the European standard EN 15978, with the Swedish version SS-EN 15978:2011. The standard applies to whole buildings and contains guidelines and methodology for construction LCA. For example, the standard stipulates attributional LCA (Boverket, 2024c). The standard divides the life cycle of a building, represented in Figure 5 into stages, presented in Figure 6.

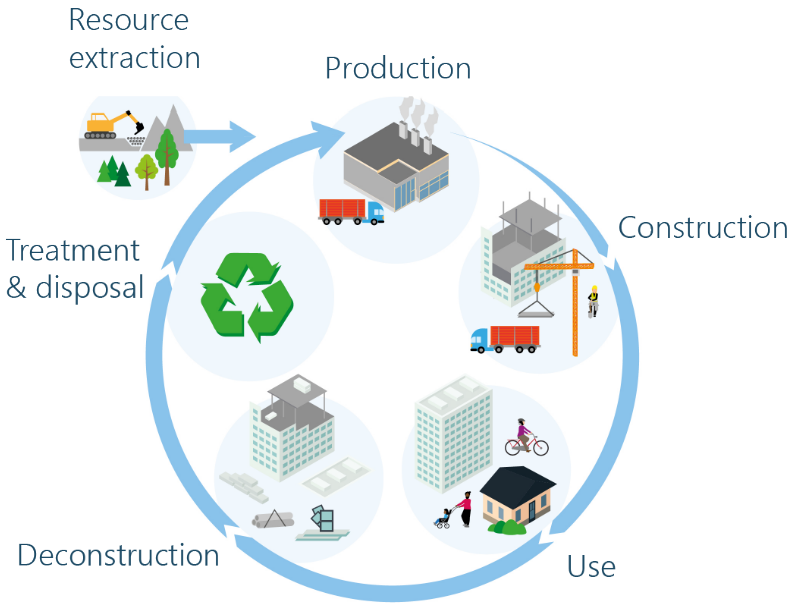
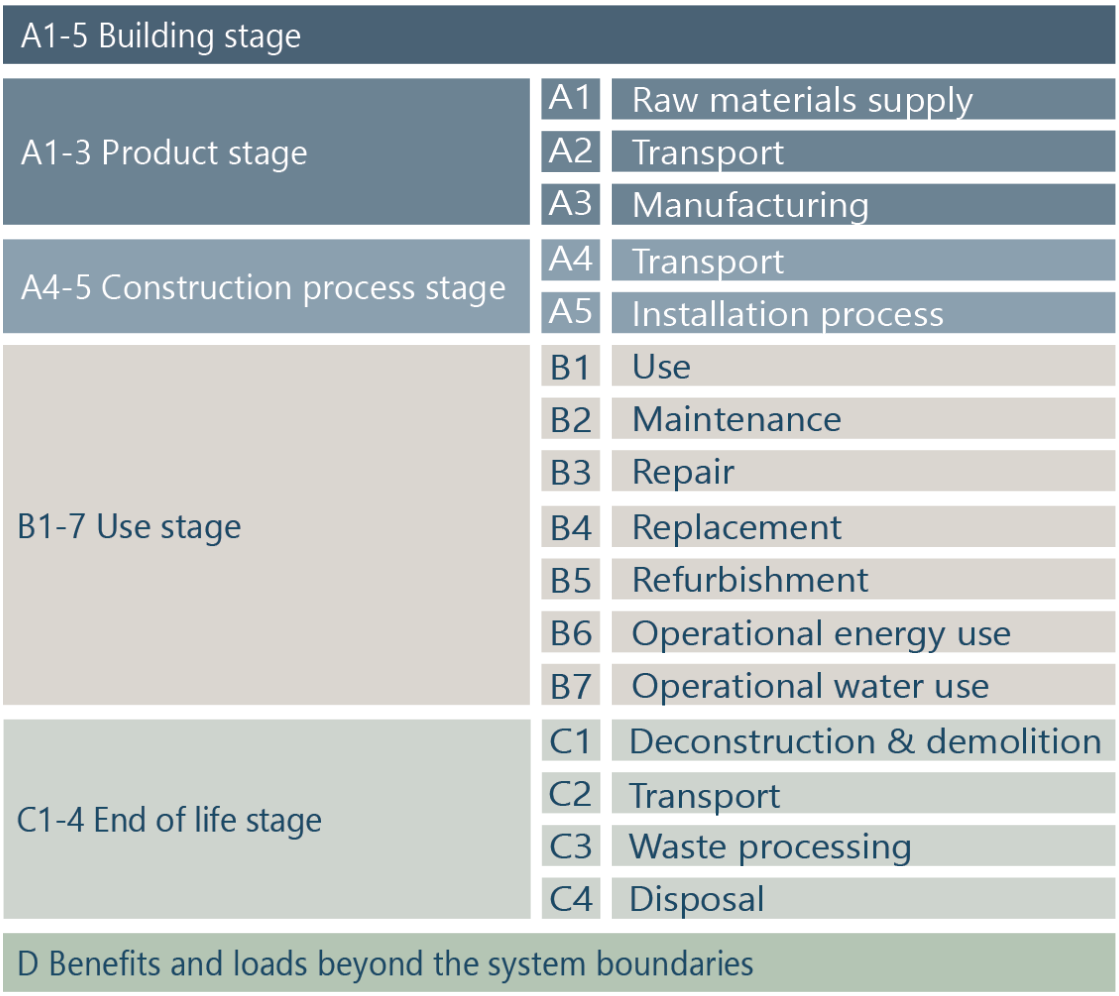


Figure 5: The life cycle of a building, adapted from Jenny Lilja/Infab/Tictac/Boverket (2024). CC BY-NC-ND 4.0



A1-5 Building stage		
A1-3 Product stage	A1	Raw materials supply
	A2	Transport
	A3	Manufacturing
A4-5 Construction process stage	A4	Transport
	A5	Installation process
B1-7 Use stage	B1	Use
	B2	Maintenance
	B3	Repair
	B4	Replacement
	B5	Refurbishment
	B6	Operational energy use
	B7	Operational water use
C1-4 End of life stage	C1	Deconstruction & demolition
	C2	Transport
	C3	Waste processing
	C4	Disposal
D Benefits and loads beyond the system boundaries		

Figure 6: Stages for building LCA, adapted from SIS (2011)

Stage A is called the building stage and is divided into five modules. Modules A1-A3 are often called the production stage, where materials and resources used in the building are sourced, transported, and produced. Modules A4-A5 constitute the building production stage, where the product transport and the building construction are included (Boverket, 2024b).

Stage B is called the use stage and is divided into seven modules. Module B1 (Use) encompasses emissions from building materials during normal use, for example substance releases from the facade of floor finishes. Module B2 (Maintenance) includes emissions from activities required for maintaining the function of a component in the building, such as floor cleaning or replacement of smaller parts of a building component. Module B3 (Repair) covers emissions from actions that repair a component to recover the function, for instance replacement of broken window glass. Module B4 (Replacement) encompasses the replacement of non-repairable components or parts at the end of life, as well as complete components with a shorter technical life span than the building itself, such as windows and partition walls. Module B5 (Refurbishment) includes extensive work to renew or repurpose parts of, or the complete, building, such as putting in partition walls to transform a building from offices to residential units (SIS, 2011). Important to know is that modules B2-B5 generally are a sum of other modules. For instance, the replacement of broken glass in a window (included in B3) should consist of modules A1-A4 for the new glass, A5 for installation, including energy, water use and waste generated, and modules C1-C4 for the disposal of the broken glass (SIS, 2011).

Module B6 (operational energy use) covers the building energy consumption in normal use, such as heating, ventilation, cooling (HVAC), lighting, water supply, pumps, etc. Other technical systems, such as lifts, escalators, and security, should be modeled as part of the operational energy use but reported independently. The module does not include energy use of non-building related appliances, and if included, the results should be reported separately. Module B7(operational water use) covers the building water consumption in normal use, for example drinking, sanitation, service hot water, irrigation, and other water systems. Water used for activities included in modules B2-B5 is excluded (SIS, 2011).

Stage C is called the end-of-life stage and is divided into four modules. Module C1 (Deconstruction and demolition) includes the takedown of the building and connected activities on- and off-site. Module C2 (Transport) includes waste transport from the site to further processing (recycling or disposal sites). Module C3 (Waste processing) covers the sorting, collection, and processing of demolition wastes at a waste processing facility. Module C4 (disposal) includes the final disposal of the building elements at a disposal site and also encompasses any actions required for preparation during disposal. Stage D is called *Benefits and loads beyond the system boundary* and covers reuse, recovery, and recycling potential (SIS, 2011).

The building stages enable uniform distribution of results, facilitating comparisons and interpretation of the outcomes. (Boverket, 2024f). Furthermore, the LCA stages are used to define the system boundaries of the assessment. Life Cycle Assessments encompassing modules A1-A3 (production stage) are labeled cradle-to-gate studies (SIS, 2011). Assessments covering modules A1-A4 (production + transport) are called cradle-to-site studies. Assessments covering module A1-A5 (production + construction) are called cradle-to-handover. Assessments covering the building stage and use stage (A and B modules) are called cradle-to-use studies. When the end-of-life stage is included, the study becomes cradle-to-grave. Finally, when all stages are included, the studies are cradle-to-cradle.

Climate declarations and Environmental product declarations (EPDs)

Since January 1st, 2022, the Swedish plan and building law states that a climate declaration is required for all new buildings. The climate declaration currently includes the building stage of the LCA (Module A1-A5), and the purpose is to reduce the climate impact of the construction. From 2027, the climate declaration is suggested to cover the whole life cycle of the building (Boverket, 2023a). The climate declaration includes the building envelope, all load-bearing construction elements, and internal walls (including other elements, such as ceilings and doors). Installations and permanent furnishings are not included (Boverket, 2024e).

The climate impact is to be calculated as the GHG emissions per m^2 of gross area (BTA) - kg CO_2-eq/m^2. The calculation method is to multiply the climate impact for a material or construction part by the amount and sum up the total for the materials, followed by dividing the total impact by gross area (BTA) (Boverket, 2024d). Generic climate impact values for common products or materials can be found in the Climate Database by Boverket (Boverket, 2024a). These can later be replaced with Environmental product declaration (EPD) values, calculated according to SS-EN 15804:2012+A2:2019 (Boverket, 2024c). An EPD is a documentation that reports the lifecycle environmental performance of a product or service. The EPD is based on LCA and enables a transparent, objective, and comparative evaluation of the life-cycle properties of a product or material. Ideally, an EPD includes the complete product system, which for construction materials means all modules (EPD International, n.d.).

Furthermore, Boverket has suggested limit values for module A1-A5 in a report from 2023, with a proposed application in 2025 (Boverket, 2023a). The suggested value for multi-dwelling residential buildings for module A1-A5 is 375 kg CO_2-eq/m^2.

2.7 Project Context

The building used in this case study was originally an office building located at Engelbrektsgatan 69 at Heden, Gothenburg. The building was recently renovated to house more offices, although this project only concerns the building before the renovation. The building and its surroundings can be seen in Figures 7 and 8.

Figure 7: Location map, adapted from Eriksson (2024)


Figure 8: *Engelbrektsgatan 69-71 (Vogler, 2017). CC BY-SA 4.0*

The building is a nine-story construction with two offset parts. The entrance is situated on the bottom floor and accessible through the pavement. The bottom floor has multiple entrances, parking, and reception. The building includes a basement and a roof level with various functions, such as a kitchen, toilets, and pavement. Floors 1-7 have the same characteristics, such as external openings, floor height, and access points. The building has a pillar-deck construction, with slabs of reinforced concrete through the entire building, supported by exterior walls and pillars throughout the building. The exterior walls are reinforced concrete and brick with window tiers in teak. The roof and ground are also reinforced concrete. The important load-bearing elements can be seen in Figure 9. The detailed construction before the transformation can be seen in Figure 10.

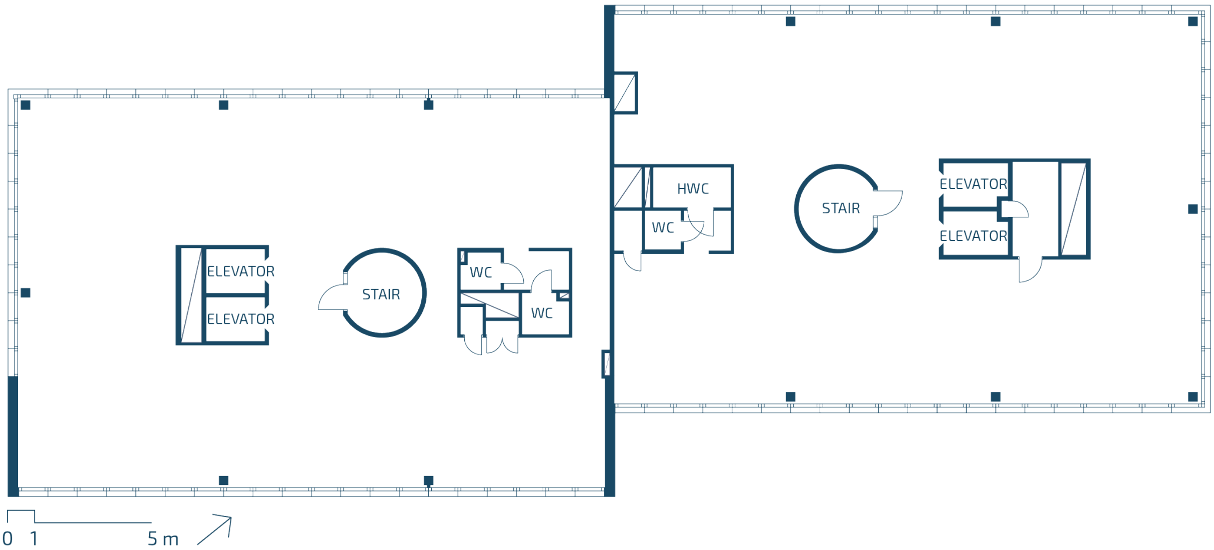


Figure 9: *Load-bearing elements, adapted from Eriksson (2024)*

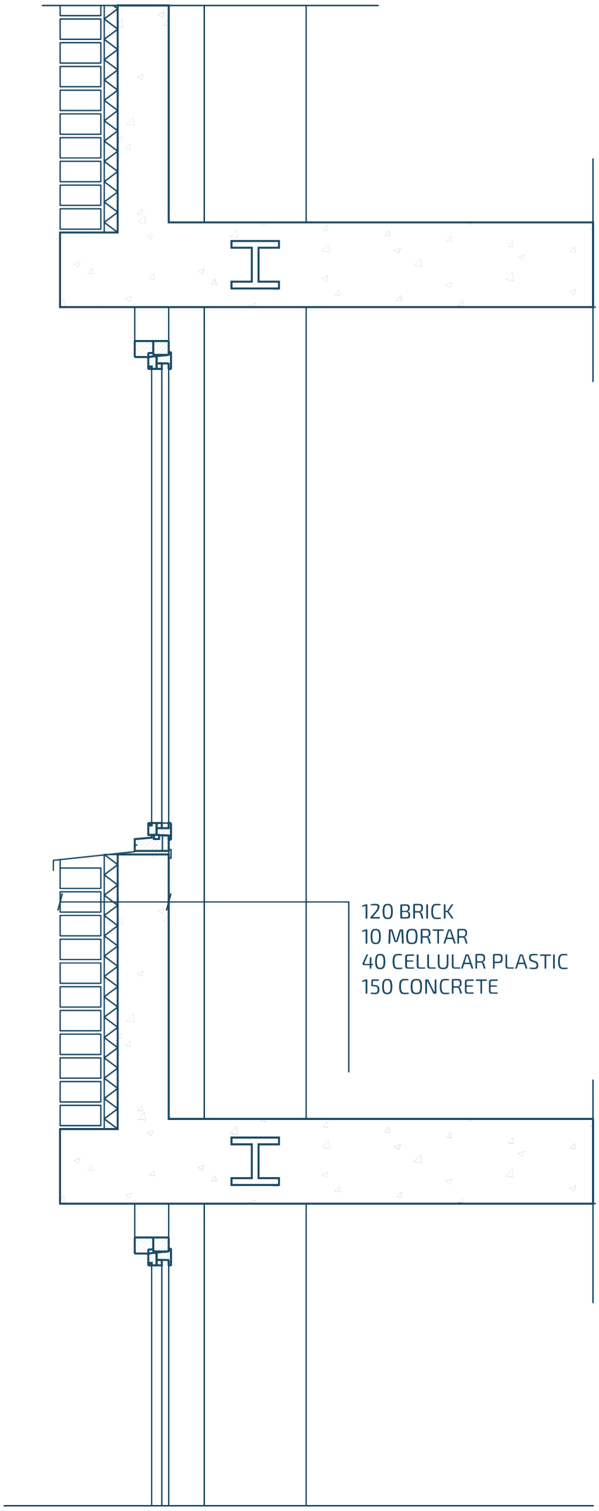


Figure 10: Construction detail, adapted from Eriksson (2024)

The author of this thesis developed a transformation project design from offices to housing with a focus on sufficiency. The project followed the previously mentioned SER framework, stipulating that sufficiency should come first. The project tested how sufficiency can be implemented and how it is affected by SS building standards. The project implemented the concepts from Figure 4 on the typical floor plan of the building. Furthermore, various aspects of transformation were investigated, such as pillar placement, preservation of bathrooms, and core placement.

This resulted in nine different floor plan layouts at the first design stage. These were evaluated using an evaluation matrix, investigating the impact of sufficiency measures on daylight, thermal comfort, carbon footprint, primary energy demand, kitchen and bathrooms, and design quality based on functionality, spaciousness, and atmosphere. The option deemed best to develop was chosen and further optimized regarding daylight and overheating, insulation, materials, etc. Important to note is that the first part of the study was performed using the original structure to see the impact of only changing the floor plan. The exterior walls were untouched except for closing openings when necessary. New walls were made with the constructions described in Figure 11.

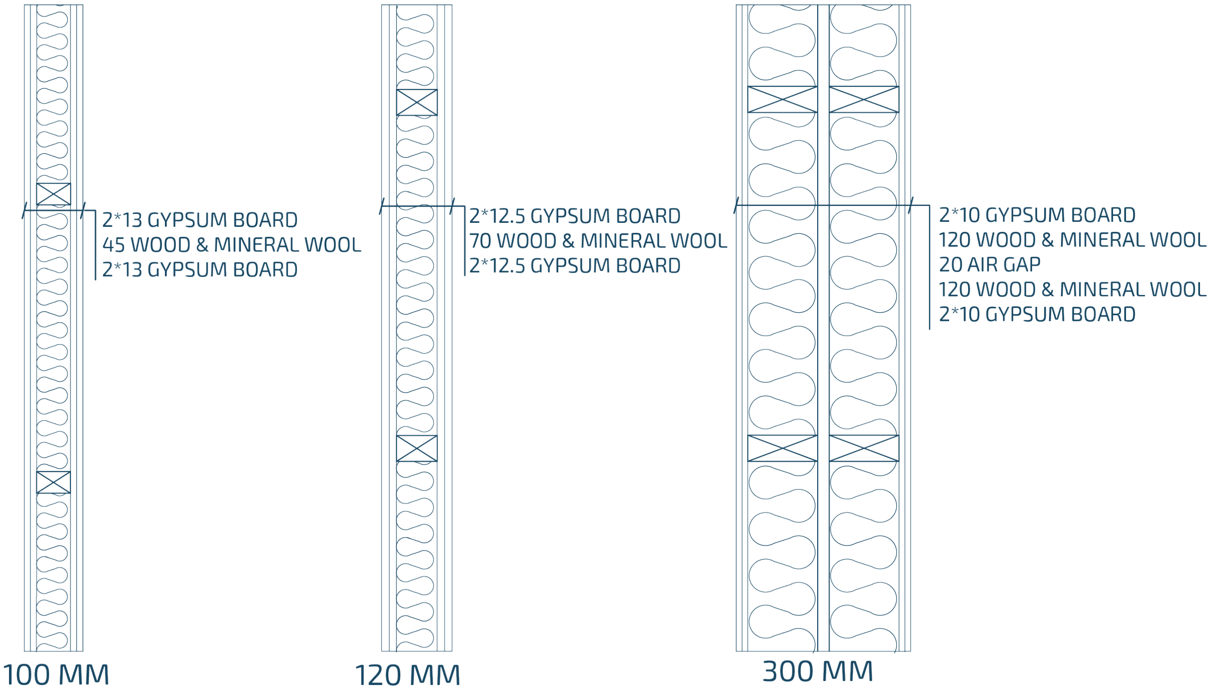


Figure 11: New interior walls, adapted from Eriksson (2024)

In the project, the roof plan has not been touched, except for adding insulation to the walls and roof. The basement was modified to hold more bike parking and less car parking. Furthermore, laundry rooms and apartment storage were added to existing storage rooms. The entrances were kept, although access points and the bottom floor were split into private and public using the multiple existing entrances. Floor 1 was turned into co-housing, hosting rentable locales, movie rooms, hobby rooms, workspaces, and guest apartments.

3 Methodology

This chapter presents and explains the methodology of this thesis. The methods and steps used for this thesis are presented in Figure 12.

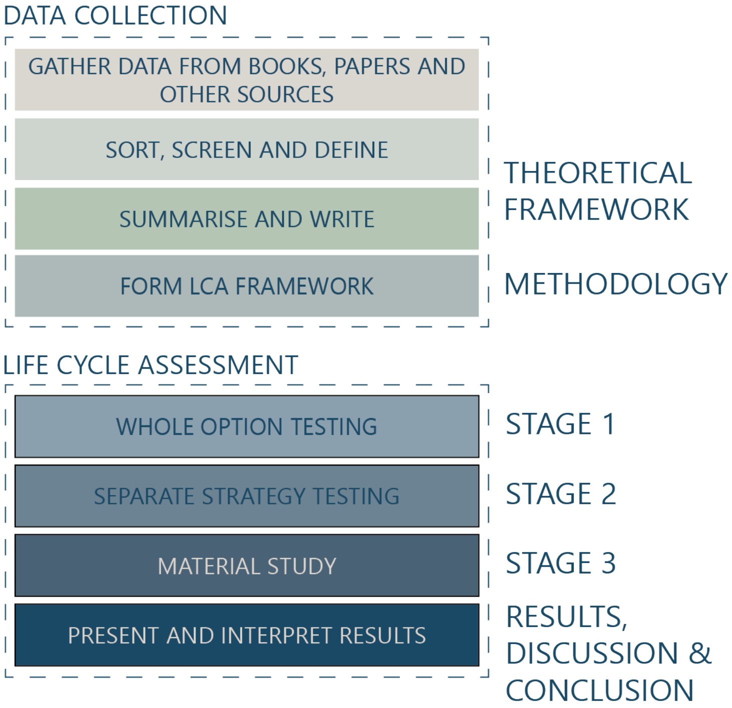


Figure 12: Thesis methodology

The thesis methodology is split into data collection and life cycle assessment. The data collection results can be seen in the theoretical background and the upcoming parts of this Methodology chapter, serving to form the framework and gather data for the life cycle assessment. The LCA is divided into three stages; whole option testing, separate strategy testing, and material study. The LCA starts by analysing six of the nine layout options developed by Eriksson (2024) in stage 1 to determine what differences can be measured using the traditional LCA approach. In the second stage, separate strategies are assessed in detail to evaluate possible measurements and the strategy's effectiveness. Furthermore, the notion of sufficiency functional unit is tested, and different functional units are evaluated.

In the third and final stage, a material study is performed to evaluate the sufficiency strategies related to material choices. Instead of the sufficiency functional unit, a comparative approach is utilized, comparing material options to determine the impact saved. The section analyses whether the effect of using bioclimatic materials is measurable when compared to other materials. Furthermore, the transformation project is compared to a new design to discover the difference in ecological footprint following adaptive reuse and determine if the effect on energy demand can be measured against the influence of material use. Moreover, this part investigates the life-cycle impact of low-maintenance materials, comparing the footprint between different materials to visualize trade-offs between impacts in different life-cycle stages.

The results are commented on after each part and are consecutively evaluated in the chapter Analysis and discussion. Hence, the presentation and interpretation of results take place in each assessment stage, as well as in the discussion and conclusion parts.

3.1 Data Collection

The data collection is performed through a literature study, focusing on various aspects. The data collection is to explain the core concepts, position them in the field of research, and establish the tested strategies. Furthermore, the data collection serves to sort the data from the previous thesis, gather references, and ensure the scientific validity of the results. The study is performed using online search engines and the Chalmers Library database.

3.2 Life Cycle Assessment

This thesis uses life cycle assessment (LCA) as the principal method. LCA is chosen because the methodology includes all aspects of the building phases, not only the use phase, which is the focus of net-zero carbon architecture and commonly also efficiency and renewables. It is a prevalent method within the sustainability community and includes important aspects of a building's life cycle, such as embodied carbon. The Grasshopper plug-ins providing LCA, energy, and water calculations give a holistic view of the life cycle building performance.

3.2.1 Goal and scope

The purpose of the study is to determine how sufficiency in the built environment can be measured using life cycle assessment. The system boundary for a complete building study, especially with a focus on sufficiency, ought to be cradle-to-cradle due to the inclusion of embodied carbon, adaptive reuse, and circularity. The functional unit sqm gross floor area (BTA) is applied to all tests, as the unit used within the database and the limit values are kg CO_2-eq/m^2. However, a research question for this study is the impact of the functional unit. Furthermore, the theory available on sufficiency in LCA suggests multiple functional units. Therefore, additional functional units are used throughout the assessment, and the measurements are stated for each stage.

The study is geographically limited to a Swedish context through the values from the database and EPDs and due to the location of the studied building. The time horizon for the study is 50 years, with the assumption of constant operational energy emissions over the time frame. Furthermore, the study is limited to the impact category of climate change, expressed through the global warming potential (GWP) in the unit kg CO_2-eq. This limitation is applied due to the limited values in the database, and the feasibility of the study within a limited time frame. Therefore, the values used from EPDs are from the category GWP-total.

3.2.2 Tools and modeling

The LCA is performed in Rhino 8 and Grasshopper using multiple plug-ins. Ladybug and Honeybee are used to set up the building climate model. Ladybug is a tool for importing relevant weather data, creating graphics, and evaluating designs using solar radiation and sunlight hours (Ladybug Tools, 2024b). Honeybee is used for daylight, energy, and thermal comfort modelling through the softwares OpenStudio and EnergyPlus (Ladybug Tools, 2024a). The Brimstone plug-in links Boverket's climate database to Honeybee within the Grasshopper interface. Brimstone is used with Heath, a panel-based UI helping the user create a Honeybee model for energy, daylight, and LCA calculations (Säwén, n.d.).

3.2.3 Model setup

The models are created in native Rhino using closed breps (polysurfaces or extrusions), with surfaces as openings. Each room is modeled as a separate brep, while the connections between openly connecting rooms are modeled as air walls. The rooms are turned into Honeybee models using Brimstone, Ladybug, and Honeybee, and each room type is assigned a separate program. Material amounts are extracted from the honeybee model, and the model is also used to calculate the demand for operational water and energy use.

Important to note is that the building modelling is limited to one typical apartment floor, including slabs, external walls, internal walls, and apertures. The modelling method results in additional building parts, such as ground, basement, entrance, roof, and balconies, being excluded. Internal doors and furniture are excluded as well.

The inputs for the LCA come from the drawings, models, and diagrams created by the author in the previous thesis. The measurements, materials, and other data come from Göteborgs Stad. The data used for the life cycle assessment comes from the Climate Database by Boverket (see section 2.6). The names and data used for materials, conversions, and climate impact of energy use come from various parts of the database. Other calculation information comes from the literature study.

3.3 Process

3.3.1 Stage 1 - Whole option testing

In this stage, six floor plans from the design stage of the architecture thesis are tested to see which results can be seen with the traditional LCA approach. The comparison of different options is made to see how well the differences show and is used as a starting point. This assessment stage uses the existing construction, with new internal walls and infiltration of 0.0006 m^3/s. The options tested are presented in Table 1.

Table 1: Chosen layout options for stage 1

Option name	Accessibility	Unit sizes	Co-living	Inhabitants per floor
Swedish Standard - small	Normal	Small	No	17
Swedish Standard - large	Normal	Large	No	24
Lowered Standard - small	Lowered	Small	No	18
Open co-living	Normal	Shared	Yes	24
Co-living - units of 3	Normal	Shared	Yes	24
International standard	No	Mixed	No	22/24

The floor plans of the chosen options are presented in Figures 13, 14, 15, 16, 17 and 18, along with short descriptions of the design qualities.

Swedish Standard - small

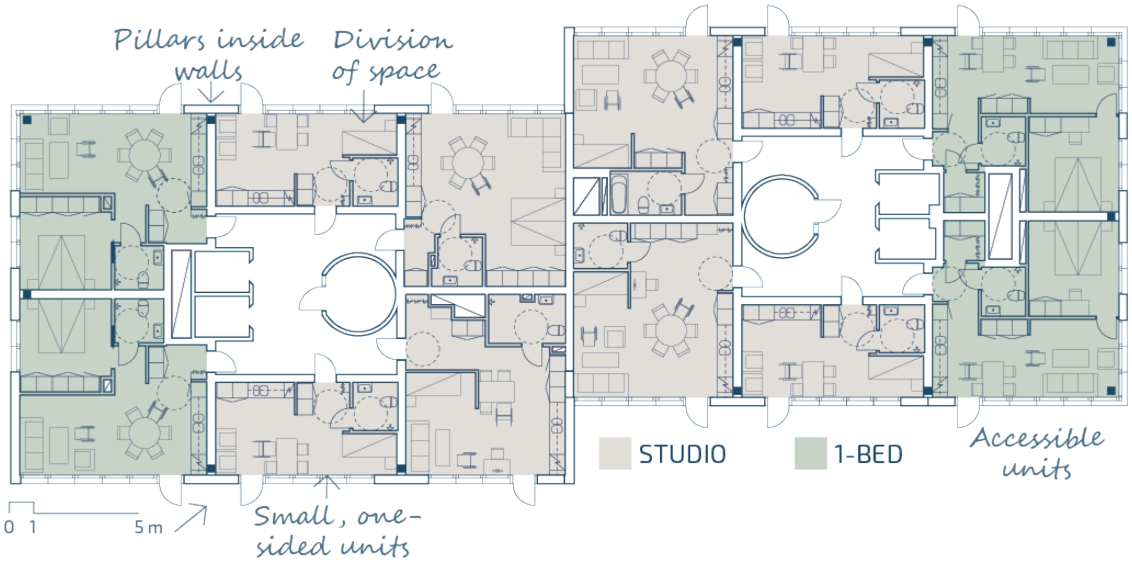


Figure 13: Floor plan for option Swedish standard - small, adapted from Eriksson (2024)

This floor plan fulfils all the criteria for normal level accessibility according to the Swedish standard. Existing pillars are put inside the apartment-separating walls so as not to interrupt the furnishable space in the apartments. The layout is an attempt to create small, space-effective units with full accessibility, serving as a test of small, one-sided apartments. A division of space separates the functions, although strongly limiting flexibility (Eriksson, 2024).

Swedish Standard - large

Figure 14: Floor plan for option Swedish standard - large, adapted from Eriksson (2024)

This layout also fulfils the normal accessibility criteria. However, pillars are partly placed within the units, enabling more freedom in the placement of units. Furthermore, an increased variety of unit types is attempted, and the layout includes larger apartments with multiple rooms. The spaces vary in size within the units, but at least one bedroom per apartment can house an accessible double bed, enabling flexible use of the existing spaces. Furthermore, this option has a smaller stairwell, giving more space to the units (Eriksson, 2024).

Lowered standard - small

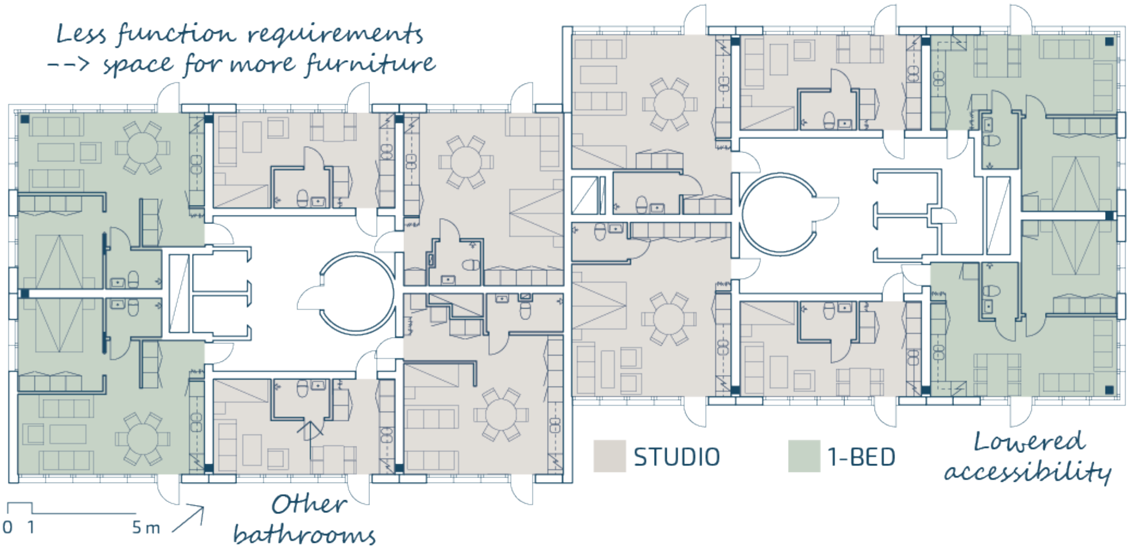


Figure 15: Floor plan for option Lowered standard - small, adapted from Eriksson (2024)

This option explores the same apartment distribution and sizes as *Swedish standard - small*, although working with lowered accessibility, meaning different function dimensions. The pillars are still placed inside the walls, and flexibility is limited (Eriksson, 2024).

Open co-living

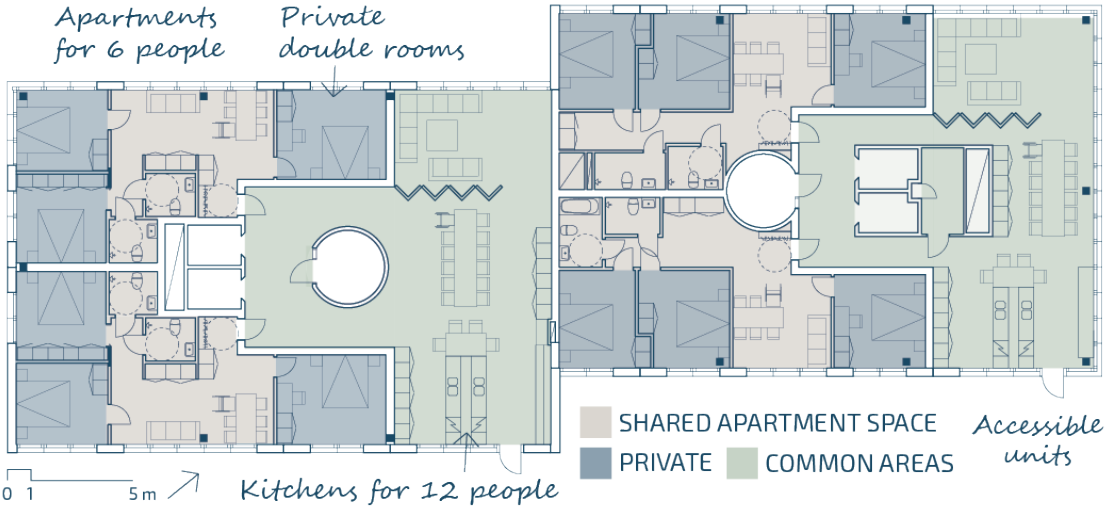


Figure 16: Floor plan for option Open co-living, adapted from Eriksson (2024)

In this option, co-living is tested following the Swedish requirement for housing with shared areas, with three people per bathroom and twelve people per kitchen. As the co-living areas are the focus of this design, they are extensive and placed in the brightest parts of the building. The bedrooms are all double, and their placement enables flexibility to rent one, two, or three bedrooms in the same space, all while sharing the common areas (Eriksson, 2024).

Co-living - units of 3

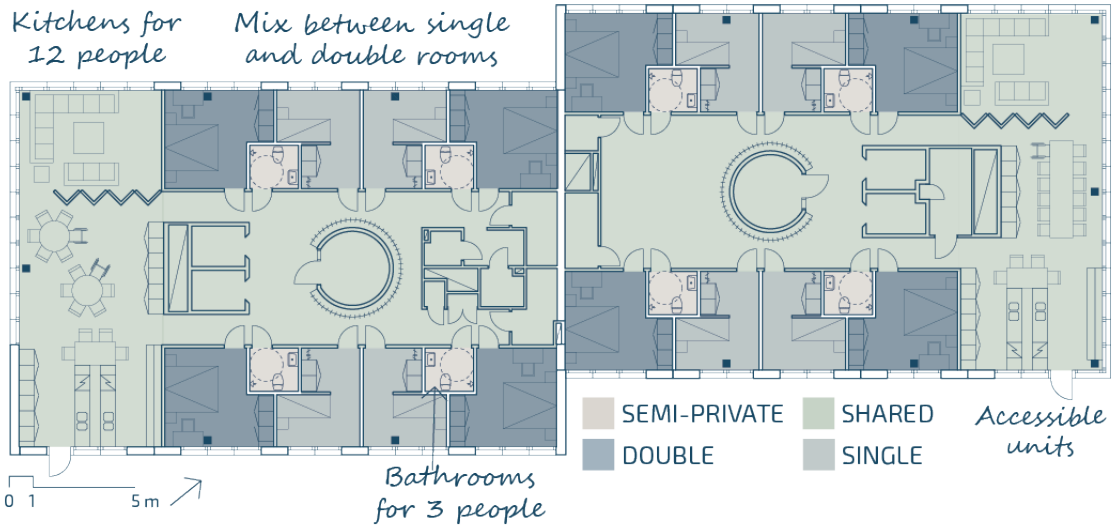


Figure 17: Floor plan for option Co-living - units of 3, adapted from Eriksson (2024)

This option plays with the classical corridor layout of shared student housing, although without private bathrooms. Instead, the bathrooms are placed in the corridor and shared by three people in two adjacent rooms. The common areas are shared by twelve people. The rooms are a combination of single and double to accommodate various users. This layout offers limited flexibility, although the units are still accessible (Eriksson, 2024).

International standard

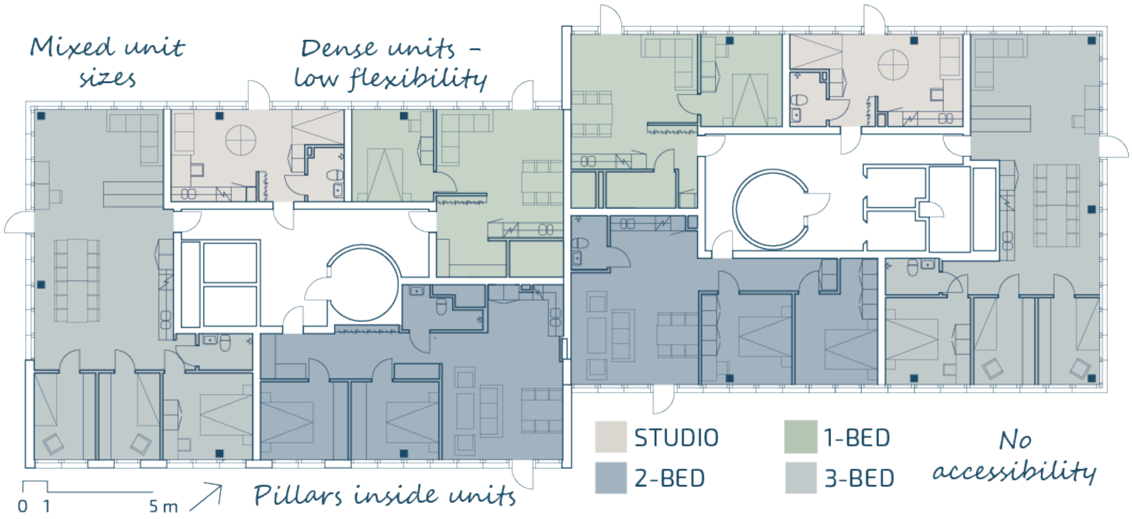


Figure 18: Floor plan for option International standard, adapted from Eriksson (2024)

This option does not follow any level of the Swedish standard. Instead, this plan has been designed more freely and inspired by international solutions. The pillars have not influenced the design layout, being entirely placed within units. This limits the flexibility within the apartments while enabling free space distribution. The unit sizes are mixed, and the lack of accessibility provides dense dwellings with low flexibility (Eriksson, 2024).

3.3.2 Stage 2 - Separate strategy testing

In this part, the strategies are tested individually to measure impact and measurability within the LCA framework. The strategies tested in this stage are summarised in Table 2.

Table 2: Strategies, functional units, reference values and models for stage 2

Strategy	Sufficiency FU	Reference value	Alternative FU	Models used
Density	Area saved	Comparison option Average dwelling area Average area/capita	Capita	*Swedish standard - small* *Swedish standard - large*
Compacity	Height factor	240 cm	Volume, m^3	*Swedish standard - small* *Swedish standard - large*
Co-living	Area factor	Comparison option	Function area, m^2	*Open co-living* *Co-living - units of 3*
Co-housing	Area factor	Comparison option	Additional area, m^2	*Swedish standard - small* *Swedish standard - large*
Flexibility	Occupancy	Full density	Time factor	*Swedish standard - small* *Swedish standard - large*

Density

This strategy aims to reduce the area per person by lowering the number or the size of rooms in a dwelling. Therefore, a good sufficiency measurement is the living area (BOA) saved per person or dwelling, measuring the impact between the design and a reference. Three different methods are tested to create a reference unit for the saved area. The first is a comparison with the average apartment sizes in Sweden based on data from 2018-2020, presented in Table 3.

Table 3: Average apartment sizes in Sweden, adapted from Granath and Nylander (2023)

Apartment size	Size [m^2]
Studio	32
1-bed	52.4
2-bed	74.3
3-bed	93.7
4-bed	115

The average apartment size limit values do not consider the number of inhabitants. Therefore, the second method uses the average living area per person, retrieved from the Swedish statistics authority Statistics Sweden. The most recent value is from 2023 and states the average living area per person as 42 m^2 (Statistics Sweden, 2024). The third method is to design a conventional option for comparison, presented in Figure 19.

For this strategy, the floor plans *Swedish standard - small* and *Swedish standard - large* were chosen, as they are different designs with the same rules and different focus regarding unit sizes. Furthermore, under the scope of this strategy, the implication of measuring impact per capita instead of per m^2 is tested.

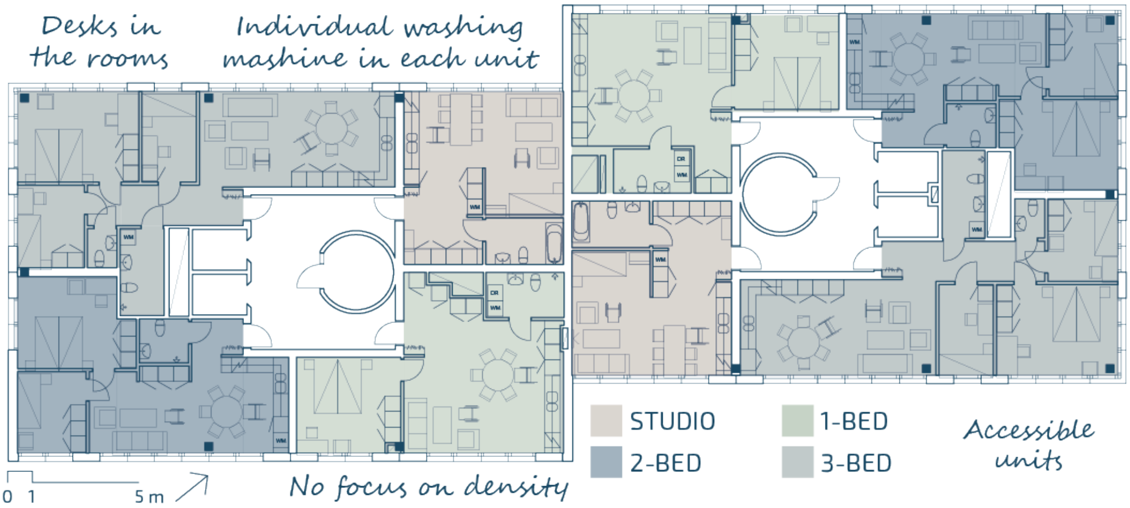


Figure 19: Floor plan for Comparison option

Compacity

Compacity aims to decrease the volume per m^2, for example by reducing the space height. According to the Swedish construction rules, the minimum space height in residential units is 2.4 m (Boverket, 2020), which is also the standard for new and existing apartments. Due to the minimum space height being equal to the standard, using the difference will not show an effect. Instead, the reference value tested here is a percentage of the standard height, describing the correlation between the modelled height and the standard (sufficiency) height. For this strategy, the floor plans *Swedish standard - small* and *Swedish standard - large* are used. The method compares the impact by increasing the height to 3.0 m. Furthermore, this strategy is used to test the implications of reporting impact per cubic meter (m^3).

Co-living

Co-living tests the effect of shared kitchens, bathrooms, and laundry. The models used are the two co-living options *Open co-living* and *Co-living - units of 3* and the comparison option. For the measuring of shared kitchens, the individual kitchen sizes are compared to the co-living kitchen sizes using total kitchen length and kitchen length per capita. The private bathrooms are compared to the total bathroom area and the area per person in co-living. For washing clothes, a shared laundry room used by the whole building is compared to individual machines. Two laundry rooms are located in the basement, shown in Figure 20. The size of these laundry rooms is compared with the total space required for individual machines, which is tested using the Comparison option presented in Figure 19.

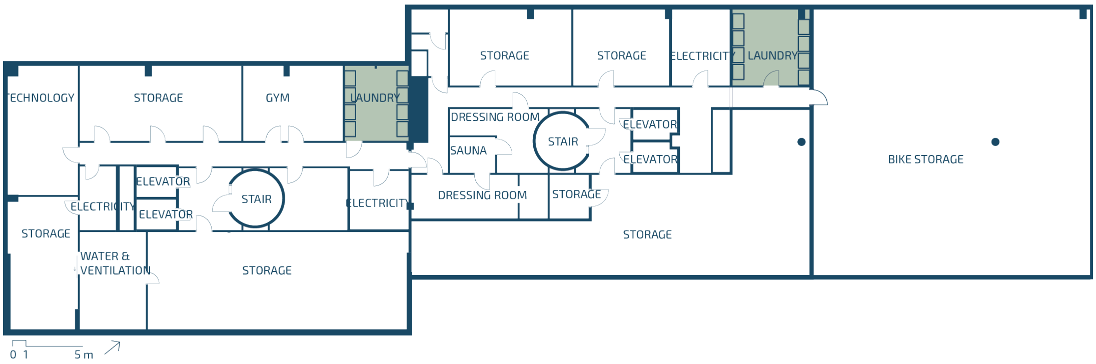


Figure 20: Basement laundry rooms, adapted from Eriksson (2024)

Multifunctionality of space through shared space

In the case study, multifunctionality is achieved by the co-housing floor shown in Figure 21.

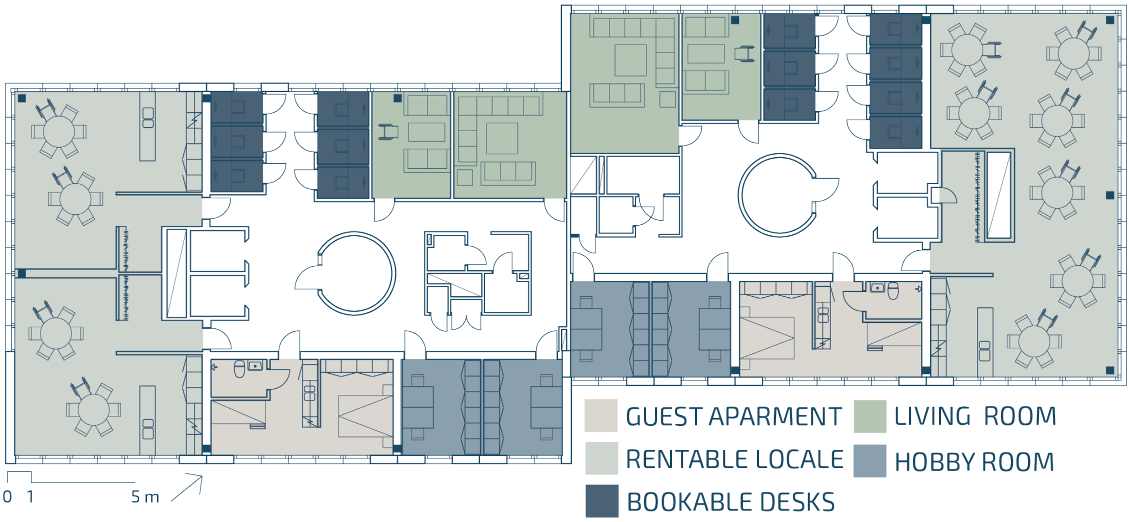


Figure 21: Co-housing floor, adapted from Eriksson (2024)

This floor holds hobby rooms, guest apartments, rentable locales, office space, and movie rooms. The area of these spaces can be compared to a case where all functions are housed within each unit, as is the case for the comparison option (see Figure 19). The differences in size between the units in the comparison option and the layouts *Swedish standard - small* and *Swedish standard - large* are multiplied by the total number of floors and compared to the area of the co-housing floor.

Flexibility

The impact of flexibility is difficult to measure. However, one way to summarise the concept is the impact of change within a unit. The goal of this test is to measure what happens when the use of a dwelling changes over time. For example, when children move out, or new users move in, this can result in a bedroom used as an office. This is modelled through occupancy, where a variety of users over time can be considered. The impact of occupancy is tested by comparing the effect of 1 person living per studio and 1-bed instead of 2 and 2 people in a 2- or 3-bed. The modelling is performed for individual dwellings using the options *Swedish standard - small* and *Swedish standard - large* .

3.3.3 Stage 3 - Material study

In this stage, the focus lies on the impact of materials and the connected sufficiency strategies. The purpose is to visualize differences in embodied carbon, maintenance, and end-of-life impacts from various materials and design alternatives. Furthermore, the aim is to measure various degrees of adaptive reuse using the whole life cycle impact of new and reused construction materials. The study does not utilize the notion of sufficiency functional unit. Instead, the implications of material choices are tested using a comparative approach, where attributional LCAs of different materials are evaluated equivalently. The goal is to see whether a life cycle assessment covering all the steps and comparing material options can show the impact saved without additional measurements. A summary of the analysis performed in this stage is presented in Table 4.

Table 4: Strategies, functional units and models for stage 3

Strategy name	Tests	Models
Bioclimatic design	Structure + Core Insulation	*Swedish standard - small + large*
Adaptive reuse	No reuse Partial reuse Full reuse	*Swedish standard - small + large*
Low maintenance	Floor covering	*Swedish standard - small + large*

Bioclimatic design

This stage includes the material aspects of bioclimatic design. For this strategy, the aim is to visualize the whole life cycle impact of nature-based materials compared to other materials. This is done by multiple comparisons of load-bearing (core and structure) and insulation materials. The impact of a wooden core and structure is compared to steel and reinforced concrete, using the dimensions of the load-bearing elements in the existing building (see Figure 9). Furthermore, the cellular plastic insulation is compared to wood fibre boards for the walls, using the required thickness for each material to reach a U-value of 0.18, as required by the Swedish Building Rules (Boverket, 2020). These studies are performed on the *Swedish standard - small* and *Swedish standard - large* floor plans, although in the context of a new building, with no adaptive reuse.

Adaptive reuse

For this strategy, the reuse of materials is compared to new materials. The study compares three alternatives: no reuse, partial reuse, and full reuse. No reuse implies a new building of the same size and function but with bio-based wood construction. Partial reuse uses the final design from the architectural thesis, which means keeping the structure, core, roof, and ground structures. Full reuse entails keeping the structure and building envelope, with only new internal walls and the closure of openings based on the new function. The constructions used for each test are presented in Figure 23 (see section 3.4). The test is performed on the *Swedish standard - small* and *Swedish standard - large* floor plans.

Low maintenance

For this strategy, different materials are compared in terms of maintenance and production costs, determining if there is a trade-off between low maintenance and operational energy use at some point. The purpose is to determine if low-maintenance materials always have a lower impact, considering the technical lifespan, production costs, and maintenance requirements. The modeling is performed for the surface layer of the floor slabs, as this is a part of the construction that faces plenty of wear and tear, requiring various degrees of maintenance. The test compares carpet, linoleum, and wooden floors to determine the impact of maintenance on the total material footprint.

3.4 Inputs

Construction and materials

For the first stage, the existing structure is used together with new internal walls. The only changes made to the exterior are the closing of openings and the addition of balcony doors. The wall and slab constructions for stages 1 and 2 are presented in Figure 22.

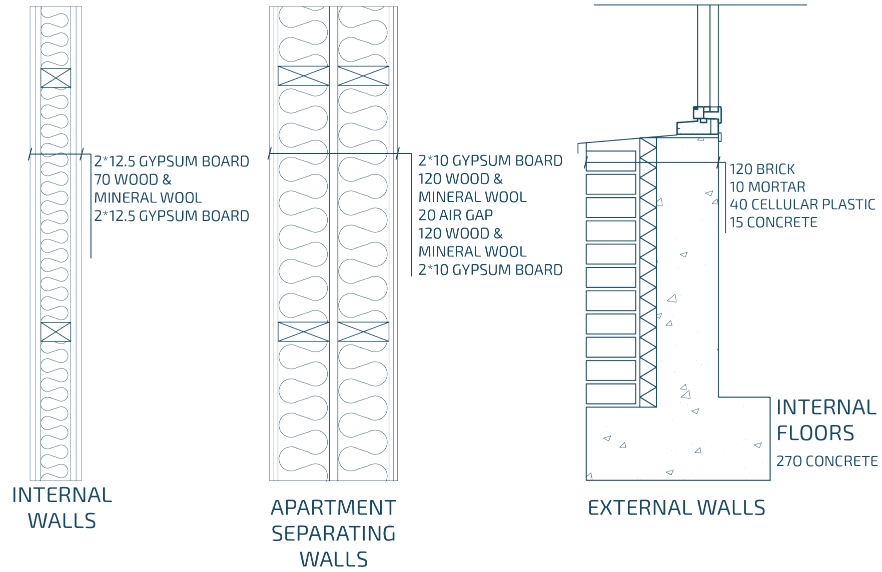


Figure 22: Wall and slab constructions used for stage 1 and 2, adapted from Eriksson (2024)

In stage 3, the constructions and materials differ for each strategy. For the strategy of bioclimatic design, the load-bearing elements are tested, meaning that the reinforced concrete is compared to wood and steel. The rest of the exterior walls are kept as is, a simplification of their likely constructions. Regarding the insulation test, the rest of the structure is kept. For adaptive reuse, three different constructions are tested, presented in Figure 23.

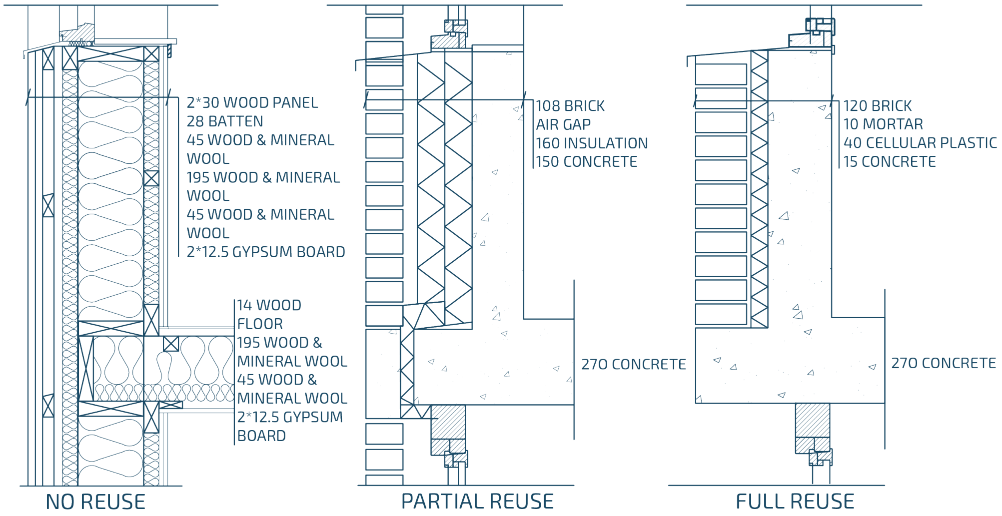


Figure 23: Wall and slab constructions for adaptive reuse strategy

For low maintenance, the existing slab is kept, and only the surface layer is changed. The materials and thicknesses for the three options are described in Table 5.

Table 5: *Thicknesses for floor coverings for the low maintenance strategy*

Material	**Thickness [mm]**
Carpet	12.5
Linoleum	2.4
Wood floor	14

Material inputs

For each material used in the stages, a correlation with the material database is established, presented in Table 6. The properties used for each material are listed in Table 7.

Table 6: *Material correlation between project and climate database*

Material	**Material in database**	**Category**
Gypsum	Gypsum, standard plasterboard	Building boards
Wood	Sawn timber, u 16%, coniferous	Solid woods
Mineral insulation	Stone wool, bats and rolls	Insulation
Wood fibre insulation	Wood fibre insulation, blowing wool	Insulation
Reinforced concrete	Ready-mix made concrete, buildings C30/37	Concrete
Cellular insulation	EPS,Expanded Polystyrene	Insulation
Brick	Bricks	Blocks and tiles
Mortar	Masonry mortar and plastering type B (CS III)	Mineral materials
Copper sheet	Copper sheet, 51% scrap based	Steel and other metals
Steel	Structural steel, 100 % scrap based...	Steel and other metals
Carpet	*Not in database*	
Linoleum	*Not in database*	
Wood floor	*Not in database*	

Table 7: *Material Properties*

Material in database	**Conductivity [W/m*K]**	**Density [kg/m^3]**	**Specific heat [J/kg*K]**
Ready-mix made concrete, buildings C30/37	1.65	2200	1000
Copper sheet, 51% scrap based	400	8900	385
Structural steel, 100 % scrap based...	40	7850	400
EPS, Expanded Polystyrene	0.035	30	1450
Bricks	0.8	1800	1000
Masonry mortar and plastering type B (CS III)	0.84	1600	1000
Gypsum, standard plasterboard	0.21	700	1000
Sawn timber, u 16 %, coniferous	0.13	455	1600
Stone wool, bats and rolls	0.035	30	1030
Wood fibre insulation, blowing wool	0.038	45	1600
Carpet	0.44	200	1000
Linoleum	0.5	1290	1000
Wood floor	0.15	500	1000

Production - Climate database:

For all materials except the carpet, linoleum, and wood floors, the production values for modules A1-A5 come from the climate database. The database contains values for categories A1-A5 per kg for common construction materials in a Swedish context, split into modules A1-A3, A4, and A5 and expressed in the unit kg CO_2-eq/kg. For the other materials, the EPD values have been used. All values for modules A1-A5 are listed in Table 8.

Table 8: Material impact values for modules A1-A5 (Boverket, 2024a)

Material	**A1-A3**	**A4**	**A5**
Ready-mix made concrete, buildings C30/37	0.145	0.0039	0.00447
Copper sheet, 51% scrap based	2.48	0.0795	0.128
Structural steel, 100 % scrap based...	1.13	0.0795	0.602
EPS, Expanded Polystyrene	4.0	0.0345	0.282
Bricks	0.314	0.0495	0.0182
Masonry mortar and plastering type B (CS III)	0.209	0.0345	0.0122
Gypsum, standard plasterboard	0.284	0.0232	0.0368
Sawn timber, u 16%, coniferous	0.08	0.0158	0.00958
Stone wool, bats and rolls	1.6	0.0345	0.114
Wood fibre insulation, blowing wool	0.241	0.0345	0.00276
Carpet	4.79	0.0259	0.0132
Linoleum	0.897	0.0968	0.310
Wood floor	-0.386	0.0462	0.0112
Reused construction product	0.0	0.0045	0.0

Use - maintenance, refurbishment, repair and replacement

The values used for module B1-B5 come from product EPDs retrieved from EPD International, and they are presented in Table 9. The full list of EPDs used can be found in Appendix 1, along with additional maintenance assumptions and sources. The technical lifespan for maintenance is 50 years, and the unit is kg CO_2-eq/kg material for all values and modules.

Table 9: Material impact values for modules B1-B5

Material	**B1**	**B2**	**B3**	**B4**	**B5**	**Actions required**
Readymix Concrete C30/37	0	0	0	0	0	None (Life span 50 years)
Copper sheet	0	0	0	0	0	None (normally not maintained)
Structural steel	0	0	0	0	0	None (normally not maintained)
EPS, Expanded Polystyrene	0	0	0	0	0	None (Life span 60 years)
Bricks	0	0	0	0	0	None (Life span 80 years)
Masonry mortar type B	0	0	0	0.259	0	15 % replaced in 25 years
Gypsum plasterboard	0	0	0	0	0	None (Life span 50 years)
Sawn timber	0	0	0	0	0	None (normally not maintained)
Stone wool, bats and rolls	0	0	0	0	0	None (Life span 50 years)
Wood fibre insulation	0	0	0	0	0	None (Life span 50 years)
Linoleum	0	4.52	0	2.76	0	Replaced in 25 years, cleaned regularly
Carpet	0	0.580	0	41.8	0	Replaced in 7 years, cleaned regularly
Wood floor	0	0	0	1.3884	0	Replaced in 25 years, no cleaning info

End of Life and Benefits and loads

The end-of-life and benefit values are also retrieved from the EPDs and are summarised in Table 10. All values are expressed in the unit kg CO_2-eq/kg of material.

Table 10: Material impact values for modules C1-C4 and D

Material	C1	C2	C3	C4	D
Readymix Concrete C30/37	0.00357	0.00925	0.000572	0.00117	-0.00264
Copper sheet, 51% scrap based	0.0000852	0.0174	0.0268	0.00000528	-0.0815
Structural steel, 100 % scrap based...	0.000610	0.0410	0.00839	0.0442	1.52
EPS, Expanded Polystyrene	0.0382	0.000801	0.00478	1.70	-0.861
Bricks	0.000609	0.000115	0	0.000717	-0.9664
Masonry mortar type B	0.00436	0.00156	0	0.00156	-0,00459
Gypsum plasterboard	0.00414	0.00313	0.0293	0.0431	-0.00453
Sawn timber	0.00049	0.01334	1.548	0	-0.232
Stone wool, bats and rolls	0	0.00312	0	0.0152	-0.0348
Wood fibre insulation, blowing wool	0.000205	0.0355	1.72	0	-0.155
Carpet	0	0.0103	0.408	0.414	-0.0377
Wood floor	0	0.149	1.62	0	-0.052
Linoleum	0.00323	0.00968	1.79	0	-0.345

Honeybee program module

For the climate model setup, the base program Midrise apartment was used, with room type Apartment or Corridor. However, the program was modified into a separate one for each room, using diverse lighting, water, and equipment values. Occupancy was set per layout. The infiltration was set to 0.0006 m^3/s per m^2 external area for existing structures, and 0.0001 for new structure. The heating and cooling setpoints used were 18°C and 28°C.

Lighting values per room:

The lightning values used in the program are based on general room requirements per type, given in lux/ m^2. These have been converted to W/m^2 using a value of 100 lux per W (Light By Sweden, n.d.). The resulting lighting values are presented in Table 11.

Table 11: Lighting values per roomtype (Karman, 2021)

Roomtype	Lux/m^2	W/m^2
Bathroom	125 + 124* = 249	2.5
Bedroom	125	1.25
Kitchen	350	3.5
Living room	200	2.0
Corridor	150	1.5
Staircase	150	1.5
Elevator	100	1.0

*A standard bathroom mirror requires 400 lux. This is divided by the minimum accessible bathroom size in the SS, which is 1.9*1.7 m. This results in a value of around 124 lux per sqm.

The use ratio is assumed to be 4.8 hours a day, simulated using a constant schedule of 0.2.

Water use per room:

The water consumption has been calculated based on the Swedish household average (Svenskt Vatten, n.d.)

- Bedroom, Livingroom, Circulation and Elevator: None
- Kitchen: 0.375 $l/h/m^2$*
- Bathroom: 1.875 $l/h/m^2$**

* The water consumption is assumed to be around 35 l/day and person for kitchens. The kitchen area is assumed to be around 4 m^2/person, which results in 0.375 l/h/m^2.

** The bathroom consumption is assumed to be around 60 l/day and person. The bathroom size is assumed to be 4 m^2. The average number of people per bathroom is assumed to be 2.5. This results in 1.875 l/h/m^2.

Equipment values per room

An average equipment use based on type, power consumption, room size and use time has been assumed. The result is presented in Table 12.

Table 12: Equipment values per roomtype (Daft Logic, n.d.)

Roomtype	**Equipment type**	**Power [W]**	**Room size [m^2]**	**W per m^2**	**Use time [h]**
Bathroom	Hairtools	100	4	25	1
Bedroom	Charging + Computer	100	10	10	6
Kitchen	Fridge, Dishwasher, Stove	3300	6	550	3.5
LivingRoom	TV and Wi-fi	60	10	6	4.8
Corridor	None	0	0	0	0
Staircase	None	0	0	0	0
Elevator	Elevator	1250	50*	25	2.4

*The building has nine floors and a basement

3.5 Hypothesis

The theory for this thesis suggests that the traditional LCA approach for buildings is inadequate in measuring sufficiency strategies. Therefore, the assumption is that for stage 1 of the assessment, only modest distinctions are visible.

For the separate strategy testing in stage 2, the assumption is that density will not be visible through the single functional unit of m^2. The estimation is that the results will be visible per capita and that the inclusion of capita or area in LCA would be advantageous. Regarding compacity, the assumption is that the effects will be indirectly visible, as the material impact and energy per m^2 is affected by the increased space height. Therefore, the volume results are likely to display the same characteristics as the metric ones. For co-living and co-housing, the effect can likely be seen traditionally. However, it would likely be beneficial to display the area/impact saved by sharing. Flexibility is difficult to quantify, but occupancy measures the effect of space change. The estimate is that this result will support the conclusion for density, with a measurement per capita or area presenting useful. Summarily, the estimation is that all strategies can be displayed to save impact, although the most significant challenges in measuring sufficiency strategies is to quantify the saved effect using reference values. Essentially, sufficiency is based on savings, and measuring savings is based on a non-saving option. Furthermore, the difference between the functional units are likely to be large, as the relationships between the functional units are vastly different. The estimation is that volume will not make a significant difference but that density and occupancy will.

For the third stage, the assumption is that the material effect can be seen using a comparative analysis. Bioclimatic design is estimated to show major differences in overall impact between constructions. Moreover, the assumption is that a trade-off between reuse and new elements can be seen, as new construction provides energy efficiency at the cost of production impact. The assumption for low maintenance is that there will be a trade-off between embodied carbon and maintenance impact and that low maintenance does not guarantee a low overall impact.

4 Results

This chapter presents the results stage by stage, along with a short description and reflection of the outcomes.

4.1 Stage 1 - Whole option testing

The results for all options are presented for all modules, production, use, end-of-life, and benefits and loads in Figures 24, 25, 26, and 27 respectively.

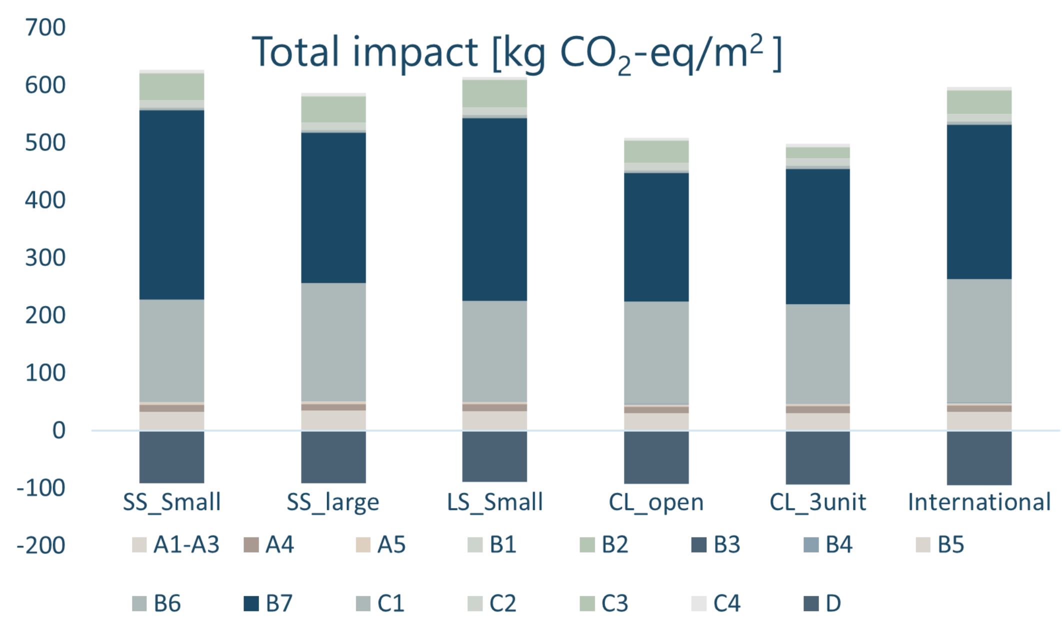


Figure 24: Stage 1 results for all modules

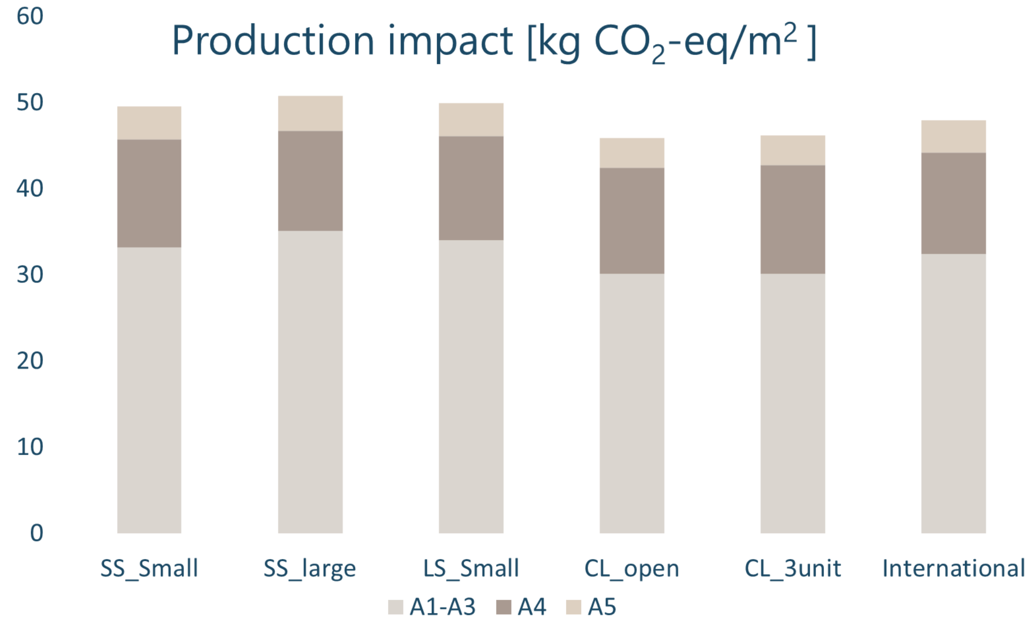


Figure 25: Stage 1 results for modules A1-A5

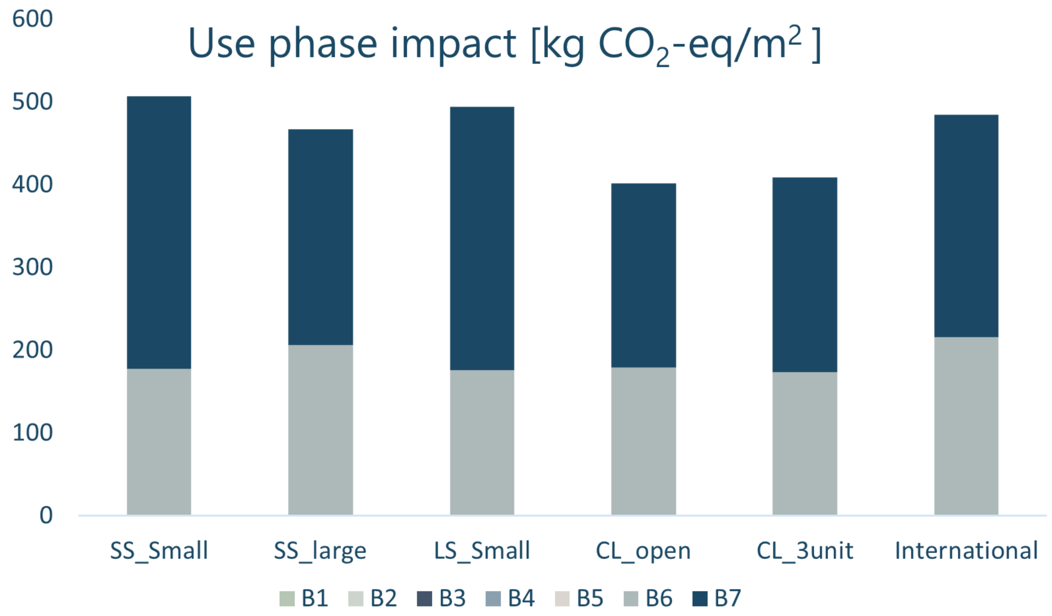


Figure 26: Stage 1 results for modules B1-B7

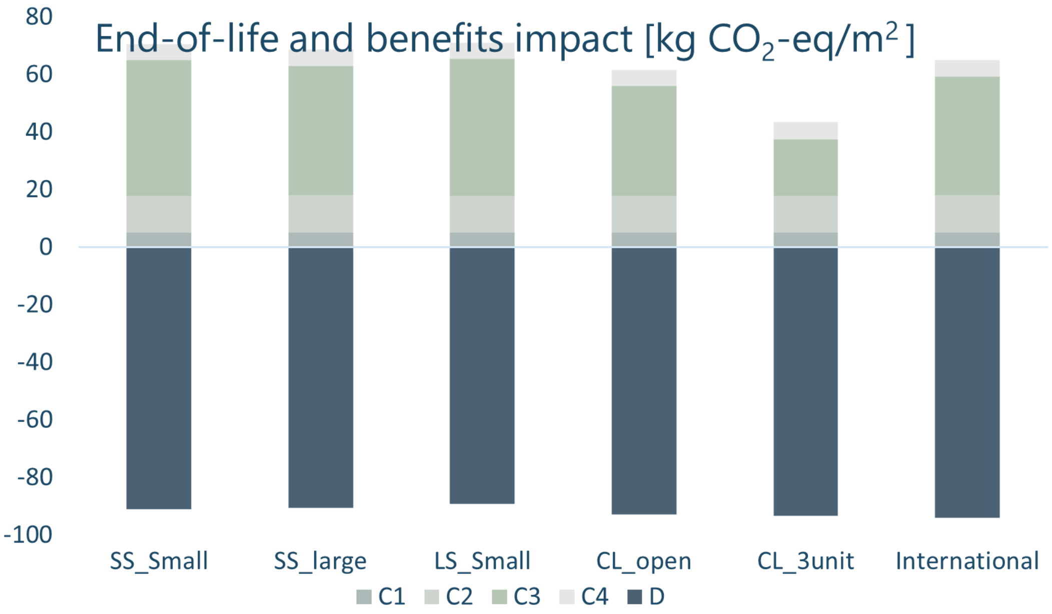


Figure 27: Stage 1 results for modules C1-C4 and D

The results from stage 1 support the hypothesis that the traceable differences using only m^2 as the functional unit are comparatively modest, confirming that impact measurement per square meter does not provide a visible representation of sufficiency strategies. The visible differences can be traced back to the reduced use of materials and the reduced operational impact of co-living, showing that the effect of co-living is slightly measurable. However, the main sufficiency target of saving area and impact through sharing is not visible. Furthermore, it can be concluded that the emissions are high from operational water use. Moreover, the water use goes down with more residents, which should not be the case as the water use is measured per inhabitant, showing that the B7 modeling could be a source of error.

4.2 Stage 2 - Separate strategy testing

4.2.1 Density

For the density strategy, the first step is to calculate the area saved for the three reference value methods. Table 13 shows the comparison with the average unit sizes displayed in Table 3, Table 14 shows the average area per person, and Table 15 shows the values obtained for the comparison option.

Table 13: Area saved compared to average Swedish apartment sizes

(a) Swedish standard - small

Unit	Reference [sqm]	Actual size [sqm]
4*Studio	32	25.2
Studio	32	40.3
Studio	32	41.4
Studio	32	41.5
Studio	32	43
2*1-bed	52.4	46.0
2*1-bed	52.4	46.2
Total	465.6	451.4

(b) Swedish standard - large

Unit	Reference [sqm]	Actual size[sqm]
1-bed	52.4	42.2
2*1-bed	52.4	46.0
1-bed	52.4	52.8
2-bed	73.4	63.8
3-bed	93.7	70.5
3-bed	93.7	72.6
3-bed	93.7	74.2
Total	564.1	468.1

Table 14: Average area per capita

Option	Total area	Inhabitants	Area per capita
Swedish standard - small	451.4	17	26.6
Swedish standard - large	468.1	24	19.5

Table 15: Total area and area per capita for Comparison option

Unit	Size [m^2]	Residents
Studio	41.1	1
Studio	41.5	1
1-bed	58.5	2
1-bed	58.0	2
2-bed	58.1	3
2-bed	58.7	3
3-bed	79.7	4
3-bed	79.1	4
Total	474.7	20
Area per capita	23.74	

The impact per m^2 and the reference area saved compared to average units sizes are displayed in Figure 28. The impact and area saved per capita compared to the average area per Swedish resident are presented in Figure 29.

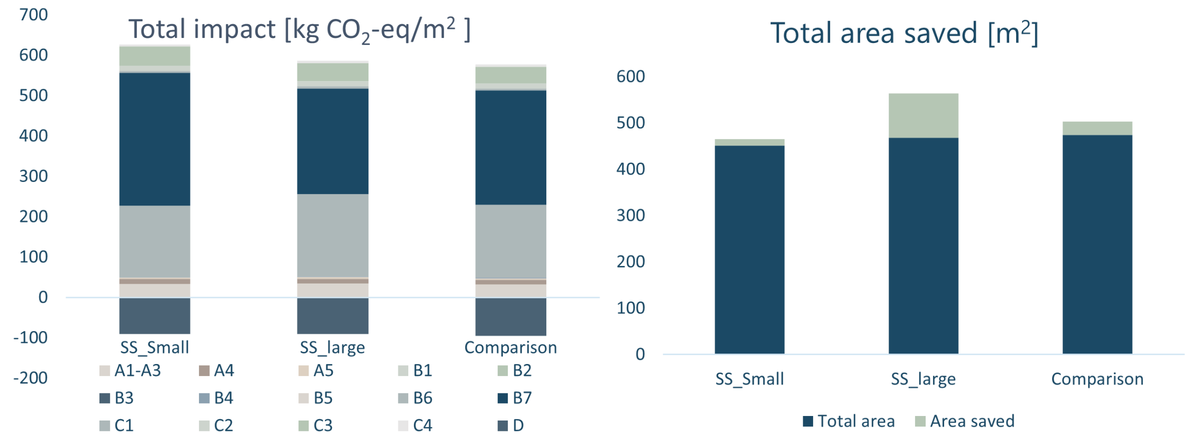


Figure 28: Density results per m^2

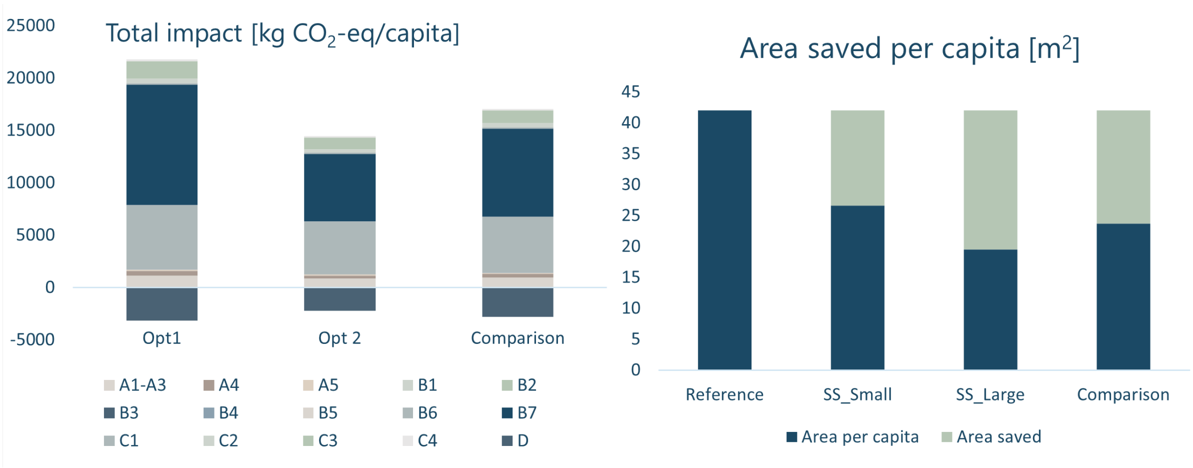


Figure 29: Density results per capita

From the results in Tables 13, 14 and 15, it can be seen that the methods for area saved give vastly different results for both models tested, as well as for the comparison option. For example, the area saved per unit and per capita differs vastly from the totals. This leads to the question of whether apartments today are fully utilized or if the occupancy is low. The results for impact per m^2 show relatively small differences. However, it can be concluded that the density is better for larger apartments, which also reveals that the layout of the reference option carries an impact. The comparison option contains a mix, including larger units, while the *Swedish standard -small* option only contains small units. Therefore, to see the full effect of a sufficiency strategy using the comparison option method, more similar layouts are required. The results per capita display a more significant difference between the options, fully highlighting the effect of the density strategy. This shows that the measurement per capita greatly influences the results and highlights the difference in characteristics for the layouts. Furthermore, the sufficiency functional unit area saved further helps to showcase the effect. Finally, it can be concluded that the reference values used for the area saved hugely influence the results.

4.2.2 Compacity

For the compacity strategy, the space height was increased by 25%. The results for the layouts *Swedish standard - small* and *Swedish standard - large* can be seen in Figures 30 and 31 respectively. The impact per m^3 is displayed in Figure 32.

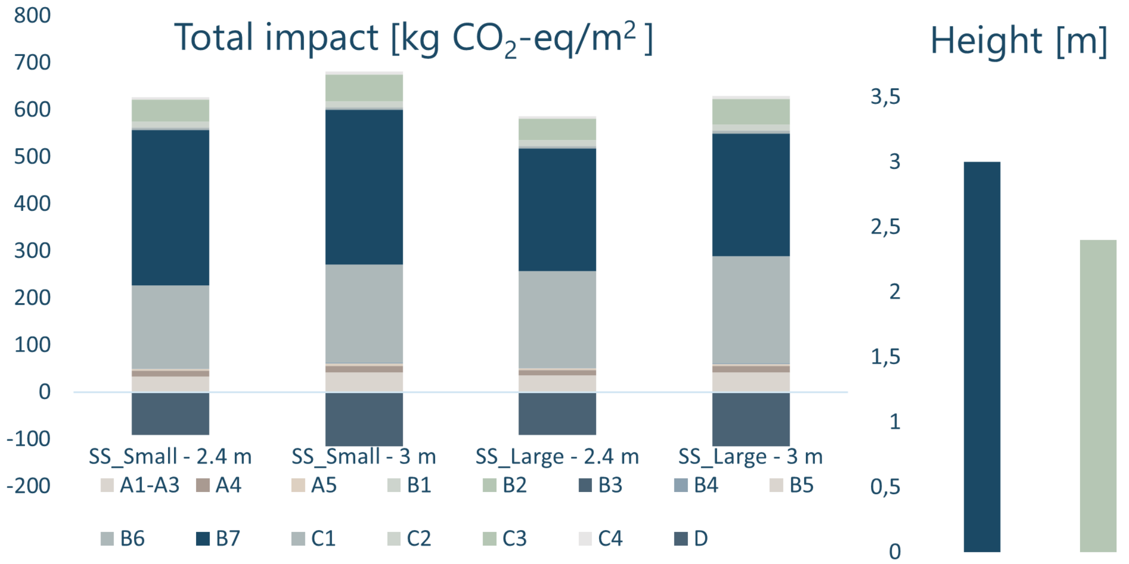


Figure 30: Compacity results for all modules

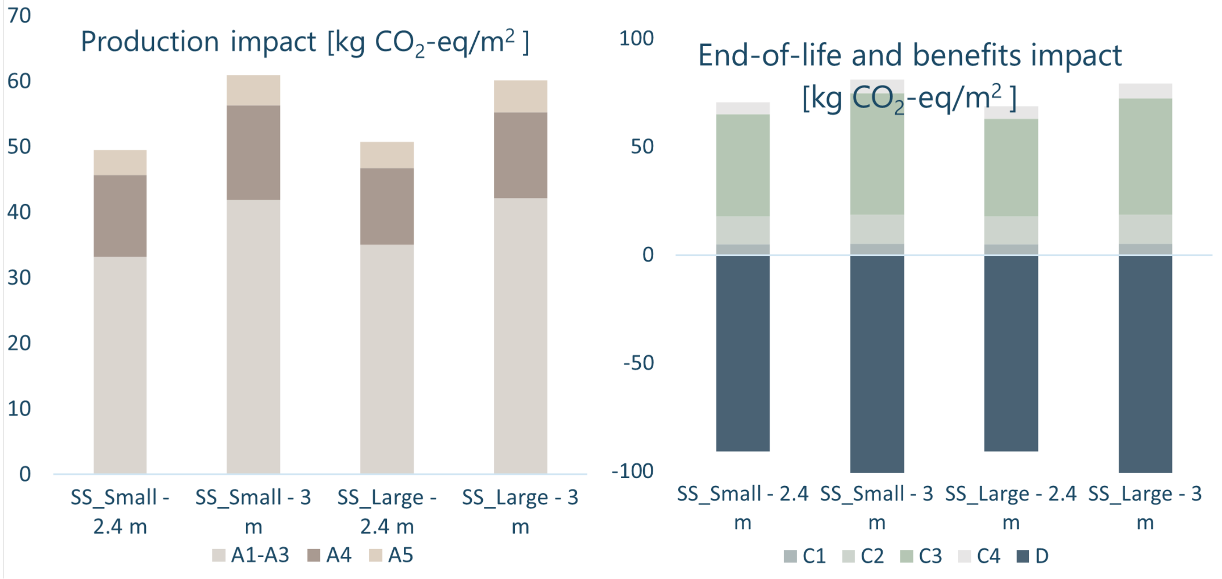


Figure 31: Compacity results for modules A and C

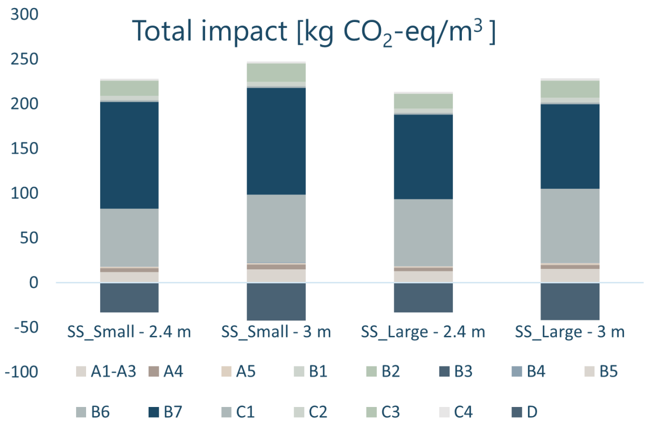


Figure 32: Volume as a functional unit

The compacity results display an increase for all modules except B7, which confirms the hypothesis that the impact from height, although not explicitly highlighted, can be seen through the traditional LCA approach. It can be noted that the height affects the impact but does not show the exact amount of savings. However, since the relative impact is similar to the height factor, it can be concluded that the extra functional unit is not crucial for measuring compacity. Regarding m^3 as a functional unit, the equivalent relation between tests can be seen as for m^2. Therefore, measuring using volume results in the same limitations as using area. Furthermore, using volume as the functional unit is unrelated to the sustainability framework and differs from the general measurement of building size. This can be motivated if the benefits outweigh the disadvantages, although this is not the case here.

4.2.3 Co-living

The co-living strategy uses the functional area as the sufficiency functional unit, with the comparison option as the reference value. The results per m^2 for layouts *Open co-living*, *Co-living - units of 3*, and *Comparison option* are displayed in Figure 33. The function area per layout is presented in total and per capita in Figure 34.

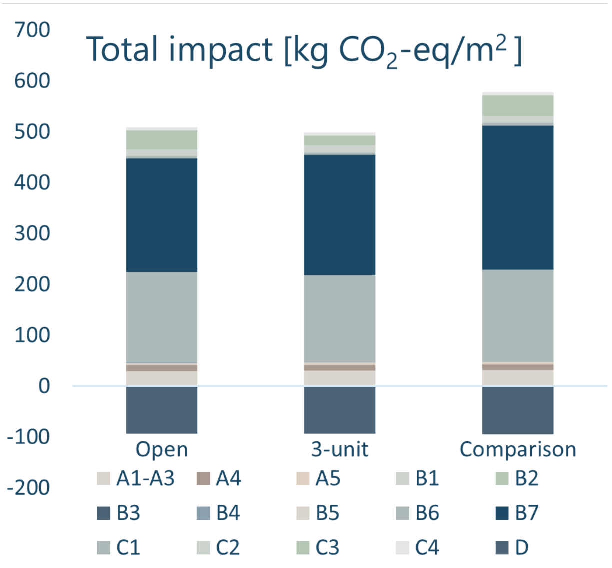


Figure 33: Co-living results per m^2

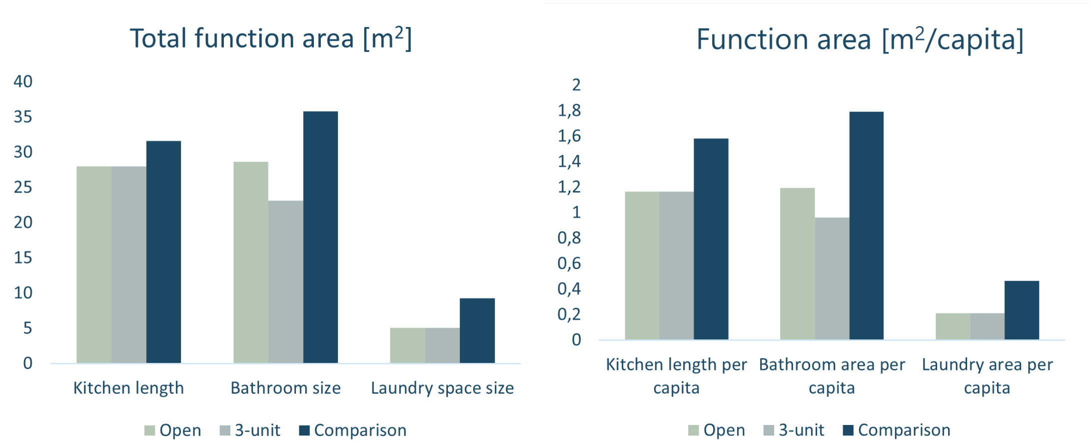


Figure 34: Co-living results for function area

The results show that co-living indeed results in a smaller area per person and lowered overall impact. Furthermore, while the total reference area shows a significant difference, the savings are even more visible when presented per capita. The results show that the effect of sharing crucial functions is visible through the sufficiency functional unit, and the combination with the functional unit capita best displays the outcome of co-living as a strategy.

4.2.4 Co-housing

The co-housing strategy uses shared area per person as the sufficiency functional unit, with the comparison option as the reference value. The total area per person and the relation between shared and individual areas are displayed in Figure 35.

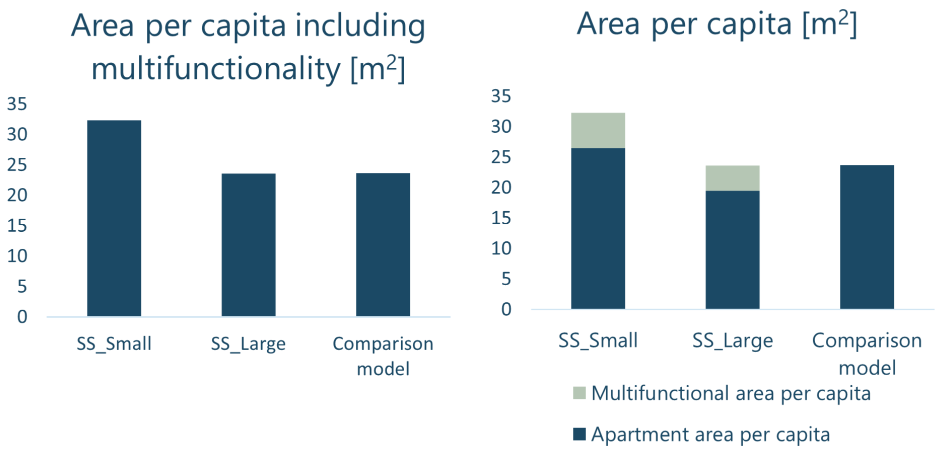


Figure 35: Multifunctionality results for total functional area and per capita

The results show that co-housing performed in this way does not result in a smaller area per person. However, the effect is still measured successfully, although the benefit of the shared locales is not visible. Therefore, it can be argued that the full benefit of co-housing is not measurable using LCA. As a measurement for LCA though, the savings (additions) can be measured through the sufficiency functional unit and the functional unit capita.

4.2.5 Flexibility

For flexibility, the impact of fewer residents was tested, simulating the effect of occupancy and changed layout. The results are presented per m^2 and per capita in Figures 36 and 37.

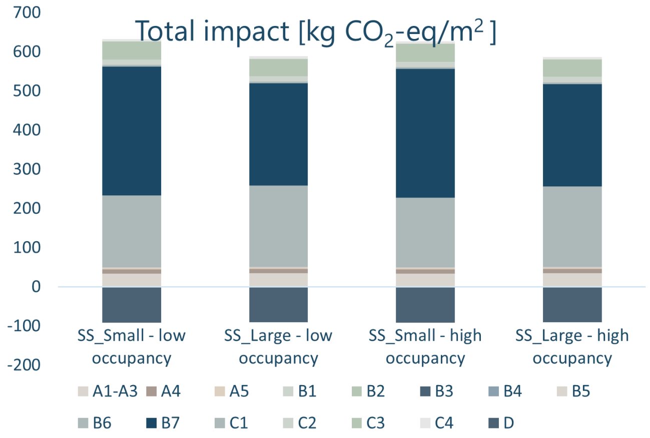


Figure 36: Occupancy effect per m^2

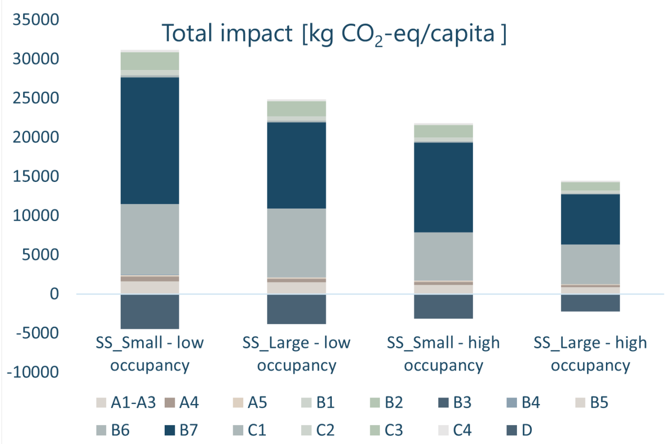


Figure 37: Occupancy effect per capita

The flexibility results solidify the importance of functional units and support the conclusions regarding reference values from the density results. Using the functional unit m^2, no differences are visible for either layout. However, using the functional area capita, immense differences are displayed. Furthermore, this shows the discrepancy between full occupancy and fewer residents, meaning that the intended number of residents and unit size do not present the entire picture of density and saved area.

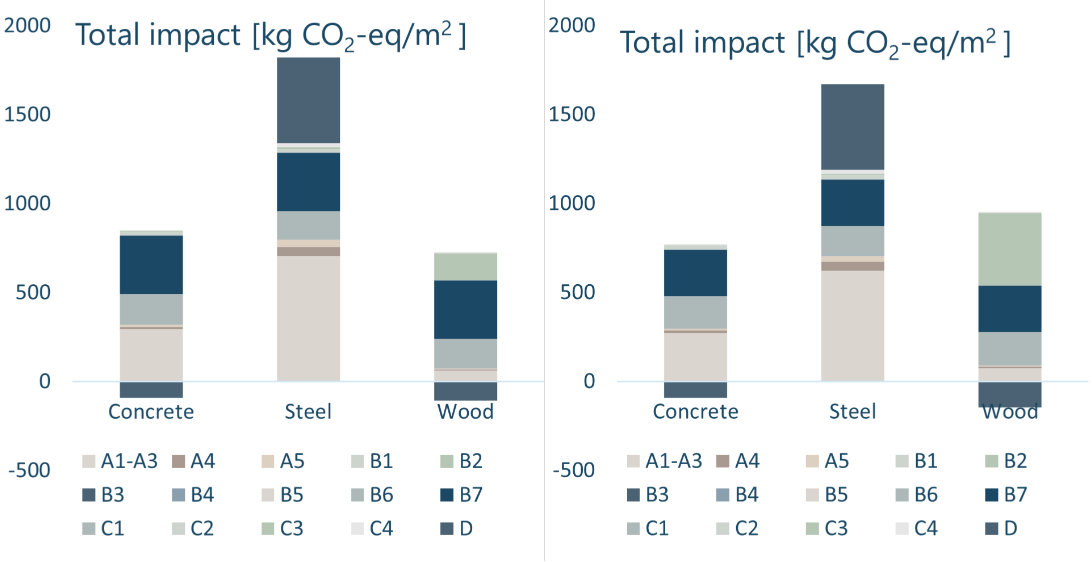
4.2.6 Summary

The stage 2 results show that a sufficiency functional or a primary functional unit measuring impact or area per capita is crucial for the evaluation of sufficiency strategies. The density and flexibility are not visible using m^2, while a slight difference can be traced for co-living. Regarding compacity, the effect can be seen both with and without the height factor. Furthermore, compacity is visible for both m^2 and m^3, and the benefits of m^3 do not outweigh the disadvantages.

4.3 Stage 3 - Material study

4.3.1 Bioclimatic design

The bioclimatic design strategy has been evaluated in two ways. The impact of core material can be seen in Figure 38, while the impact of insulation material can be seen in Figure 39.



(a) Swedish standard - small

(b) Swedish standard - large

Figure 38: Comparative core impact for bioclimatic design

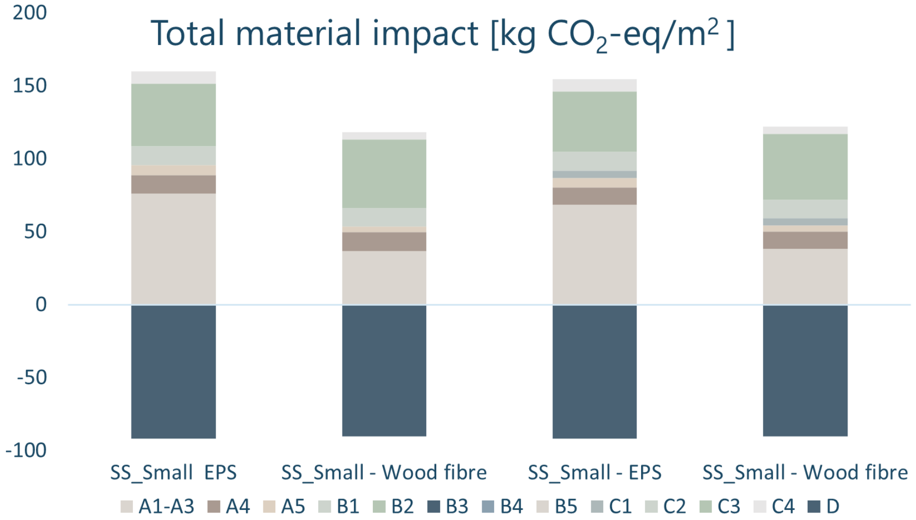
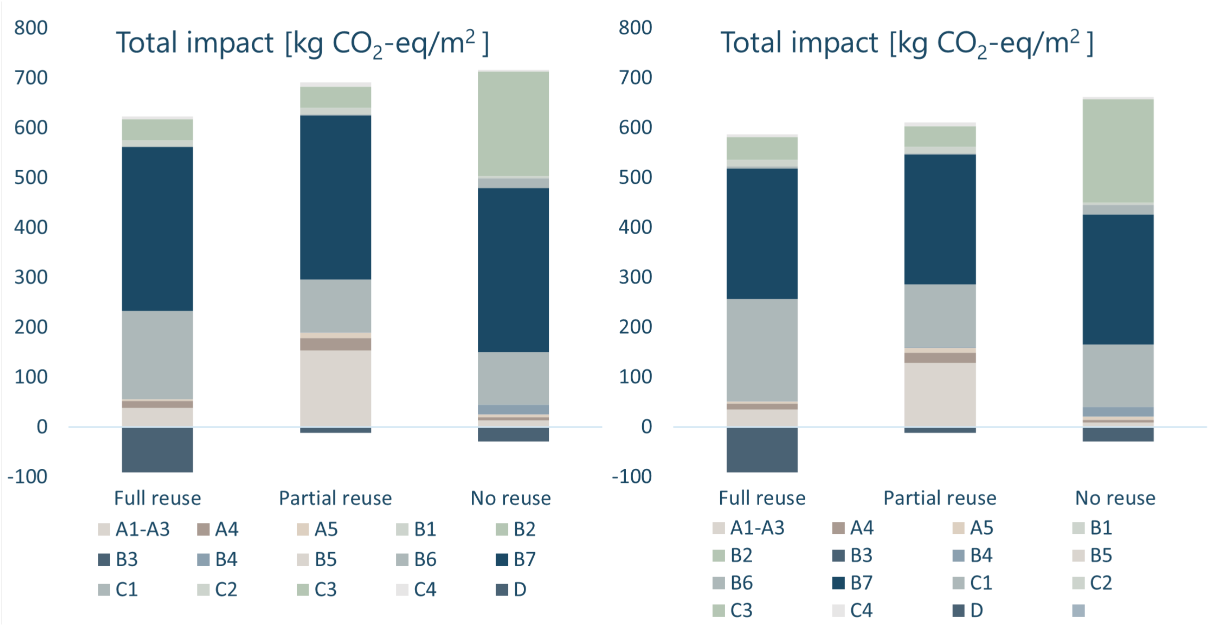


Figure 39: Bioclimatic insulation impact

The results exclude the operational energy and water use, as there is no difference between the tests. The results show that the impact of material choices can be measured using a comparative approach, similar to a consequential approach. Furthermore, the results show that the inclusion of all modules is important. In the structure results the total values would be vastly different if module D is excluded, which is common in LCAs. The test confirms that bioclimatic design is successful in lowering impact and measurable using LCA when compared to other materials and if all modules are included.

4.3.2 Adaptive reuse

Reuse is tested for three comparative options, and the results are displayed in Figure 40. As module B7 is independent of material use and impact, the operational water use has been excluded.



(a) Swedish standard - small

(b) Swedish standard - large

Figure 40: Adaptive reuse impact

The results show the differences between reuse options in total and per module, supporting the notion that a comparative material study can show impact saved compared to other constructions. However, for full transparency and improved measurement of savings, a measurement for the extent of reuse could be included. Furthermore, a trade-off between embodied and operational impact can be traced, as full reuse has a lower production impact but provides increased operational emissions through transmission and infiltration losses.

4.3.3 Low maintenance

The material impacts per m^2 for the three materials included in the low maintenance are displayed in Figure 41.

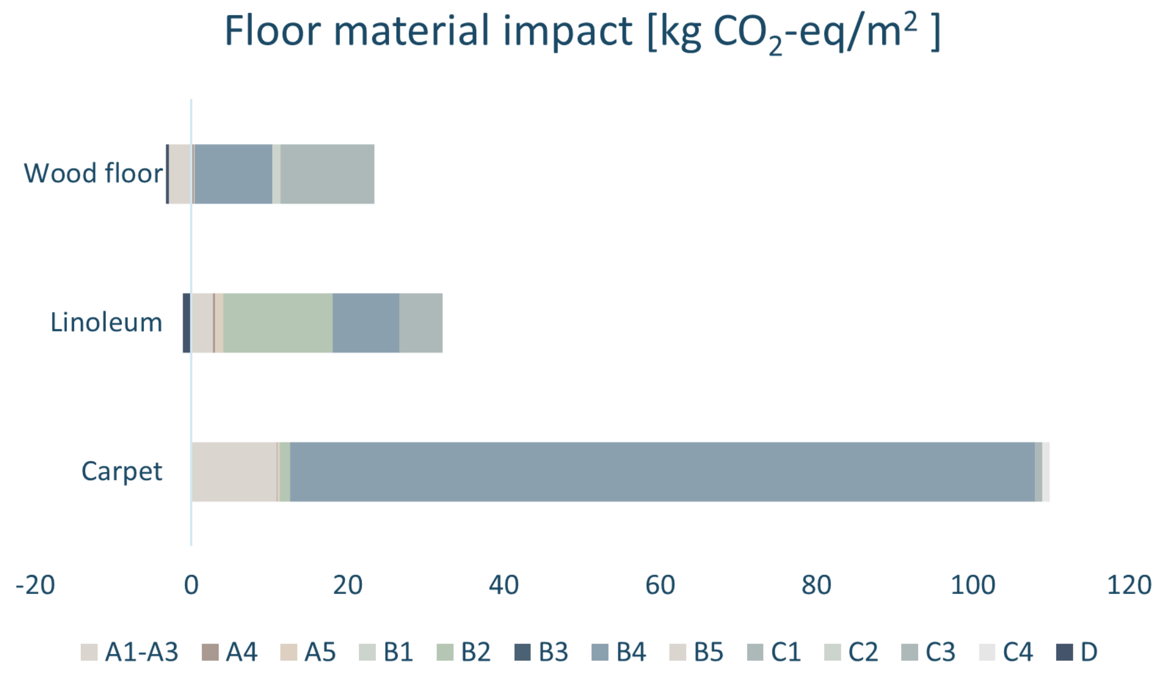


Figure 41: Floor material impact per m^2

Here it can be noted that, opposite to the hypothesis, low maintenance does result in low overall impact. A trade-off between low impact in the use phase and decreased production costs can not be seen. The results show the importance of EPDs, as maintenance for materials is possible to measure as long as modules B1-B5 are included. For the wood floor, module B2, a significant part of the life-cycle impact for linoleum, is excluded. Furthermore, the importance of methods can be seen here, as the context of the results becomes crucial. The most significant difference between linoleum and wood floor is found in module C3 and comes from a difference in end-of-life processing. The wood floor is recycled, while the linoleum and carpet are incinerated, showing a trade-off between the impact of recycling compared to the impact of new materials.

4.3.4 Summary

The results show that the traditional attributional LCA approach can assess the material impact and related strategies, although the effect of the sufficiency strategies is only visible when compared to other materials. Multiple trade-offs regarding sufficient material use can be seen between life cycle stages at various points.

5 Analysis and discussion

This chapter covers an analysis and discussion of the results and methods. Following the structure of the research questions, the chapter starts with evaluating the assessment of sufficiency strategies. Next, the functional units assessed and the effect on the results are discussed, followed by the analysis of the measurable trade-offs. Subsequently, the methods used, limitations, and possible sources of deviations are discussed. Finally, recommendations for further inclusion of sufficiency are presented.

5.1 Evaluation of sufficiency strategies

As expected, supported by the background and hypothesis, the first stage of the assessment, performed using traditional building LCA, does not show any considerable differences. A slight difference can be seen between the co-living and individual unit options, which comes from the reduced energy use of appliances. The most significant difference between the options tested is the density, which varies from 16 to 24 inhabitants per floor. The effect is not shown at any point in the LCA results, highlighting the problem with measuring sufficiency and the limitations of using m^2 as a functional unit.

In the second part, separate strategies are tested using the notion of Sufficiency LCA. For density, the sufficiency unit area saved shows that the size varies greatly depending on the reference value. The savings are comparatively modest when comparing dwelling sizes, while extensive differences can be seen using the overall average area per inhabitant. Moreover, this is also reflected in the results from the flexibility tests, measuring the impact of reduced occupancy in dwellings. This highlights the difference between resident capacity per unit and the number of inhabitants, showing that occupancy and the actual number of residents vastly impact the effect of sufficiency. Furthermore, the use of a conventional comparison option highlights the difficulty of traditionally comparing results. The comparison option shows a reduced impact per m^2 when the sufficiency functional unit is excluded, supporting André's theory that a reduction in functional output would cause an increase in emissions per functional unit. The density results highlight that measuring impact per capita shows substantial differences in density not displayed using the m^2 as a unit. In summary, the density and flexibility results clearly show that a density/occupancy measure would greatly benefit the measuring of sufficiency strategies in building LCA.

The compacity results show the expected outcome that an extra sufficiency unit measuring volume or height is not necessary. The relative factor between the increased height and the tested height is reflected in the relative increase of impact. Results can be seen in every part except the water use, which is not affected by the size but by the number of residents. Furthermore, this shows that a measurement per volume unit would be obsolete, as everything but the water use is impacted by the height. Regarding co-living and multifunctionality, the results show that using functional area and functional area per capita is advantageous for assessing the effect, especially compared to a conventional design. This further strengthens the notion that area per capita or capita should be included as a measurement in LCA. However, for multifunctionality, it can be argued that LCA can measure the tangible area savings, but the use of the functions is not included.

For stage 3, a comparison between two attributional LCAs is performed instead of including a sufficiency functional unit. The comparison highlights the impact saved through the modeling of two attributional LCAs. The results show that using other materials and constructions for comparison works. However, the relation between them might be challenging because the constructions might contain different amounts to achieve the same properties. Furthermore, the results also show the importance of including all modules in an LCA, as the material impacts can change notably depending on the scope of the study. The bioclimatic design results show that the inclusion of all modules is crucial, as the exclusion of a module can vastly impact the comparative results. Furthermore, the test confirms the possible measurement of materials through comparative analysis and that bioclimatic design is a successful strategy.

For adaptive reuse, the no reuse option, which would provide the most energy-efficient building and use biobased materials, gives the highest impact from production. Partial reuse keeps the structure but replaces the bricks due to material damage, offering a more balanced difference between embodied and operational carbon. Full reuse provides the lowest embodied impact, although providing an immense spike in operational energy use. Furthermore, as concluded by Eriksson (2024), reuse can be complicated since it can be challenging to know the state of material without extensive research, and full reuse might not be possible due to damage or extensive transmission losses. One potential solution is that a percentage of reuse is shown and that a comparison between new materials and reused ones can provide a measurement of the impact saved. This should be used with caution, however, as the production impact per reused construction product is considered zero, which might not be the case (see further in Sections 5.4 and 5.5).

The maintenance results show a trade-off between embodied and operational, but that over the lifetime of the building, low maintenance does not necessarily give a lower life cycle impact. The measurability of maintenance requires the inclusion of the use phase in the LCA itself and in all EPDs, which is not the case today (see Section 5.5). Furthermore, how the results are interpreted and presented has a great effect on the visibility of material maintenance. Breaking down the separate material impact into modules highlights the difference between materials regarding the different life cycle stages. Hence, it is shown that low maintenance can be measured, but only with the appropriate graphs and all modules included in the LCA.

Summarily, the results show a varied measurability for sufficiency strategies. It can be concluded that some sort of comparison is required for all sufficiency strategies. Doing a conventional attributional LCA will not show any savings. Although, some measurements will reduce the impact in an attributional LCA without comparison. For example, reuse will reduce the absolute material impact per m^2, although it will not be measured how much. Therefore, the suggestion is to compare with other materials for the stage 3 strategies and to include a measurement to show the area/demand saved per capita.

5.2 Functional unit

As proposed by the theory and supported by stage 1 analysis, the functional unit m^2 does not register the most significant density strategy. Only using the mm^2 as the functional unit does not display the building size, function, or properties. Furthermore, in a housing context, impact per m^2 does not show how many people live in the building and the size of the units. With this said, m^2 is a comprehensible unit for comparison, suitable for comparability and generality. The evaluation of monitoring impact per capita and density values shows that a measurement per capita can immensely impact the overall results, showing an extensive difference between the options that could not be seen using m^2. Measuring impact per capita, or somehow displaying the area per inhabitant and area saved, provides a sizeable difference and can be used in addition to m^2.

Regarding the measurement of impact per volume, this did not serve to highlight the emissions saved by sufficiency. The effect of building height could be seen using m^2 as well, and as it turns out, m^3 has the same difficulty in measuring size and function. Furthermore, with m^2 being the standard unit, an idea of the size of the apartment and the functions included can be grasped by the user. However, a m^3 measurement becomes rather abstract. The volume of an apartment does not indicate the characteristics of an apartment, as the floor area could vary significantly with a single volume measurement. The conclusion is that building volume (m^3) as the functional unit does not provide increased measurability of sufficiency. Instead, it makes it less relatable, and a more concatenated number makes it harder to understand the characteristics of the apartment.

The notion of a sufficiency functional unit works for measuring the effect of sufficiency, especially regarding density, flexibility, and co-living. However, in some cases, such as compacity, an additional functional unit is rendered obsolete as the strategy effect is measurable using a single attributional LCA. Furthermore, reference values have a great impact on the effect of the sufficiency functional unit, and it can be challenging to decide on measurement values. The conclusion is that including capita as a functional unit, displaying area per person or area saved would be beneficial, while regarding materials, a comparison between multiple attributional LCAs is a better choice.

5.3 Trade-offs

In the results, and also in the theory, a trade-off between density and flexibility of space can be seen, with the occupancy strongly impacting the design. Flexibility requires space and might provide larger spaces or apartments with extra rooms to ensure functionality over a building's lifetime. However, non-flexible units might cause a need for more buildings and extensive renovation in the future. Here, a trade-off can be seen between the current, measurable need and consecutive effect and the future, more unknown needs for adaptable spaces. The trade-off can be summarised as current impact vs future resilience. The current impact can be measured (although difficult), while future needs are problematic to measure. How can you measure the emissions saved from a future building or renovation you don't even know you need?

Furthermore, a trade-off between material use and impact, circular material use, and maintenance can be traced. Higher material impact from production can give lower maintenance requirements and subsequent emissions. A material might require more maintenance, although the overall material impact, including maintenance, is still lower over the lifetime of the construction. Hence, low-maintenance materials might not always be the best solution, as the low impact during the use phase can come at the cost of a higher production and end-of-life impact.

Finally, a trade-off between embodied and operational carbon can be traced regarding adaptive reuse. Keeping the structure can seem like the option with the lowest impact, as no production of new materials is required. However, this might be at the cost of operational emissions, as older structures might have more infiltration and transmission materials due to lower U-values or aging of materials. A new, energy-efficient low-carbon construction can therefore be better than reusing the existing building from an emission perspective. Important to note, however, is that material use and depletion of natural resources are not included here. With that said, the possible trade-off for reuse in the building sector is clearly visible in this study.

5.4 Assessment inputs and limitations

The main method used for this thesis is LCA. The study has been performed in a Swedish context, with Swedish or European reference values, and in a Swedish climate. However, since this study evaluates the possible measurement of differences, the results can likely be generalised to a global context. The comparative evaluation of what is visible or not would not be affected as long as the goal and scope, methods, and tools are consistent. Therefore, using climate change as the only impact category can arguably have a more prominent impact on the study. The inclusion of other impact categories, such as depletion of natural resources, would likely significantly impact the results. Currently, the conclusions of this study only apply to climate change effects, which is a sizeable limitation for the generality of the thesis.

Regarding the modeling, the study is limited to one typical floor of the chosen building, excluding ground, roof, and non-typical floors. This likely has an impact on the results and the comparability between them. Modeling only one floor provides a smaller test base, and the relative impact of errors becomes larger. Furthermore, the impacts from roof and ground constructions are neglected. Moreover, assumptions for climate, lighting, electrical appliances, etc impact the results of the operational energy assessment. However, as this is not the focus of this study, the impact can be considered moderate.

The material input values for the various models are mixed between general and specific ones. Furthermore, there can be discrepancies between EPDs regarding methodology for the underlying LCA, which can be seen in the low-maintenance test. Therefore, the exact relationship and the size of differences and trade-offs are uncertain. However, the uncertainty can be considered moderate, as all values still apply to the chosen material to some degree. Another source of error that has been clear in the results is the modeling of the operational hot water use. However, as this is a comparative study, and the hot water use is unaffected by most strategies tested, the source of error can be considered minor.

This thesis can also be seen as biased towards sufficiency, as the author has previously written a thesis stipulating sufficiency. However, with the new scope of this thesis and a focus on measurability and not design quality, the impact can be considered low. The life cycle assessment studies performed in this report are not related to the success of sufficiency or a quantitative measurement of exact impact. It only aims to determine whether or not the effect can be quantified.

Finally, a few characteristics regarding the input data can be discussed. The climate database values assume an impact of zero for reused construction materials, which strongly impacts the results. This can be seen as a simplification to facilitate the calculation of impact from reused products and a way to promote reuse within the construction sector. However, this makes the data uncertain, as the values are independent of the construction's initial effect. This is calculated as if the impact does not apply to reuse since the production costs have already been accounted for. However, this might not always be the case, and this is a simplification that affects the reuse data in favour of reuse. Furthermore, the use of EPDs in this project has highlighted another issue with the input and consequential results. In many EPDs, the use phase and required maintenance are excluded or assumed to be zero due to the technical service life of the product. This changes the scope of the studies and excludes part of the life-cycle impacts. Furthermore, as the values are independent for each material, this can affect the overall differences between materials as well as the results of this study.

5.5 Future needs

This study highlights possible implementations for the evaluation of sufficiency for LCA in the building sector. A few key points are highlighted as crucial for measuring impact, such as the inclusion of a density measurement. This could be the area per capita or the number of inhabitants or units within the project. Another key point is that the reporting of modules B1-B7 in EPDs needs to be improved, as the use phase is excluded or assumed to be due to the service life of the material or product.

Regarding the measurement of the effect or impact saved by sufficiency strategies, it can be concluded that both a sufficiency functional unit and the comparison options work rather well. The largest difficulty is to have something to compare to, with reference values "proven to have an immense impact on the result. The values could be compared to the suggested limit values of the Boverket report or a sustainability framework, although the difficulty with that is comparing buildings of different sizes and properties. Therefore, more research on reference values and sufficiency functional unit in general would be beneficial to ensure the validity of the evaluation of sufficiency.

Finally, it would be beneficial to expand the climate database by Boverket with more modules and materials. The database is helpful for general studies such as this one, where specific product values are not required. The mix of values from the database and EPDs provides a source of error, highlighted in stage 3 by the difference in modular impact. An extension of the database would also ensure increased reporting of the use phase impact of materials and lay the foundation for a further spread of building LCA in Sweden.

6 Conclusion

The last chapter presents the conclusions of the thesis. It is divided into four sections, where the three research questions are revisited one by one and finished with the author's final words.

How can LCA evaluate sufficiency in architecture in a comparable, visual, and holistic way?

This thesis evaluates two ways of measuring sufficiency in LCA: an additional functional unit tested on unit and surface-related strategies and a comparative analysis performed for material-related strategies. Both are functional, although they are highly dependent on the reference values. Therefore, for the inclusion of these methods in LCA, qualitative reference values need to be used. Finally, including area per resident or other density measures would benefit the inclusion of sufficiency strategies in early-stage LCA for the building sector.

How does the choice of functional unit influence the LCA of sufficiency strategies?

This thesis tests multiple functional units, along with the addition of a sufficiency functional unit. The results show that the impact is immensely different depending on the functional unit and that a sufficiency functional unit is successful. It can be seen that m^3 has a low relative impact on the results, while capita and other area measurements capture differences from density, co-living and co-housing, and flexibility.

What are the possible trade-offs between embodied and operational impact when implementing sufficiency in the residential sector?

This thesis shows that multiple trade-offs can be found when implementing sufficiency in the residential sector, especially regarding material choices. While incorporating reuse in construction, trade-offs can be seen between saved embodied carbon impact and possibly improved energy efficiency. Furthermore, a trade-off can be seen between production and recycling, where the method for end-of-life processing can immensely affect the total life-cycle impact. Finally, when working with flexibility, although hard to quantify, there is a possible trade-off between current operational impact and future embodied impact, showcasing the difficulty of incorporating sustainability in a holistic, resilient way.

Final words

There is promising progress in the inclusion of sufficiency in the building sector in general and in LCA. The next step is to create incentives for sufficiency strategies, which this thesis aims to support. I hope that you have gained some insight into the possibility of measuring sufficiency and what the positive effects on a project could be. Sufficiency needs to be a crucial tool included in all building projects, and this report shows how the impact can be traced. Sufficiency and LCA are cornerstones of the transition path to a sustainable future, and I hope this thesis inspired you to be a part of the journey.

References

Akenji, L., Bengtsson, M., Toivio, V., Lettenmeier, M., Fawcett, T., Parag, Y., Saheb, Y., Coote, A., Spangenberg, H., Capstick, S., Gore, T., Coscieme, L., Wackernagel, M., Kenner, D., & Kolehmainen, J. (2021). *1.5-Degree Lifestyles: Towards A Fair Consumption Space for All*. Hot or Cool Institute, Berlin. https://hotorcool.org/wp-content/uploads/2021/10/Hot_or_Cool_1_5_lifestyles_FULL_REPORT_AND_ANNEX_B.pdf

André, H. (2024). If less is more, how you keeping score? Outlines of a life cycle assessment method to assess sufficiency. *Frontiers in Sustainability*, *Volume 5 - 2024*. https://doi.org/10.3389/frsus.2024.1342223

Barrutieta, X., Kolbasnikova, A., Irulegi, O., & Hernández, R. (2023). Decision-making framework for positive energy building design through key performance indicators relating geometry, localization, energy and PV system integration. *Energy and Buildings*, *297*, 113442. https://doi.org/10.1016/j.enbuild.2023.113442

Baumann, H., & Tillman, A. (2004). *The Hitch Hiker's Guide to LCA : An orientation in life cycle assessment methodology and application*. Studentlitteratur.

Bierwirth, A., & Thomas, S. (2015). Almost best friends: sufficiency and efficiency. Can sufficiency maximise efficiency gains in buildings? *Eceee summer study proceedings*, *1. Foundations of future energy policy*, 71–82.

Boverket. (2020). *Boverkets byggregler (föreskrifter och allmänna råd). BFS 2011:6. t.o.m. BFS 2020:4*. Boverket. https://forfattningssamling.boverket.se/detaljer/BFS2011-6

Boverket. (2021). *Förutsättningar för omvandling av lokaler till bostäder* (2021:3). Boverket. https://www.boverket.se/globalassets/publikationer/dokument/2021/forutsattningar-for-omvandling-av-lokaler-till-bostader.pdf

Boverket. (2023a). *Gränsvärde för byggnaders klimatpåverkan* (2023:20). Boverket. https://www.boverket.se/globalassets/publikationer/dokument/2023/slutrapport-gransvarde-for-byggnaders-klimatpaverkan.pdf

Boverket. (2023b, July 12). *Underhåll*. https://www.boverket.se/sv/PBL-kunskapsbanken/teman/kulturvarden/kulturvarden-i-plan---och-bygglagen/krav-pa-byggnadsverk-och-tomter/underhall/

Boverket. (2024a, January 25). *Boverkets klimatdatabas*. https://klimatdatabasen.boverket.se/

Boverket. (2024b, July 3). *Introduktion till livscykelanalys (LCA)*. https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/livscykelanalys/introduktion-till-livscykelanalys-lca/

Boverket. (2024c, July 3). *Standarder för LCA*. https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/livscykelanalys/miljodata-och-lca-verktyg/standarder-for-lca/

Boverket. (2024d, September 25). *Beräkna byggnadens klimatpåverkan*. https://www.boverket.se/sv/klimatdeklaration/gor-sa-har/berakna/

Boverket. (2024e, September 25). *Byggdelar som ingår*. https://www.boverket.se/sv/klimatdeklaration/gor-sa-har/byggdelar-som-ingar/

Boverket. (2024f, September 25). *Klimatdeklarationens omfattning*. https://www.boverket.se/sv/klimatdeklaration/gor-sa-har/omfattning/

Braide, A. (2019). *Dwelling in time: Studies on life course spatial adaptability* [Doctoral dissertation, Chalmers University of Technology]. Chalmers Research. https://research.chalmers.se/publication/509729

Brändström, J., & Saidani, M. (2022). Comparison between circularity metrics and LCA: a case study on circular economy strategies. *Journal of Cleaner Production*, *371*, 133537. https://doi.org/10.1016/j.jclepro.2022.133537

Cabeza, L. F., Bai, Q., Bertoldi, P., Kihila, J., Lucena, A., É. Mata, É., Mirasgedis, S., Novikova, A., & Saheb, Y. (2022). *Buildings*. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.011

Cambridge University. (n.d.-a). Co-housing. In *Cambridge dictionary*. Retrieved January 4, 2025, from https://dictionary.cambridge.org/dictionary/english/co-housing

Cambridge University. (n.d.-b). Co-living. In *Cambridge dictionary*. Retrieved January 4, 2025, from https://dictionary.cambridge.org/dictionary/english/co-living

Daft Logic. (n.d.). *List of the Power Consumption of Typical Household Appliances*. https://www.daftlogic.com/information-appliance-power-consumption.htm

Dounis, A., & Caraiscos, C. (2009). Advanced control systems engineering for energy and comfort management in a building environment—A review. *Renewable and Sustainable Energy Reviews*, *13*, 1246–1261. https://doi.org/10.1016/j.rser.2008.09.015

EPD International. (n.d.). *The international EPD system*. https://www.environdec.com/about-us/the-international-epd-system-about-the-system

Eriksson, L. (2024). *Efficient renewable sufficiency - a dense office transformation for resilient affordable housing* [Master's thesis, Chalmers University of Technology]. Chalmers School of Architecture. https://projects.arch.chalmers.se/wp-content/uploads/2024/06/erikssonlina_19960_3506207_Eriksson_Lina_BDTS_MT-2024-Booklet.pdf

Erlandsson, M., Ekvall, T., Lindfors, L.-G., & Jelse, K. (2014). *Robust LCA: Typologi över LCA-metodik - två kompletterande systemsyner* (B-rapport ; B2122). IVL. https://ivl.diva-portal.org/smash/record.jsf?pid=diva2%3A1552422&dswid=4117f

Fischer, C., & Grießhammer, R. (2013). *When less is more - Sufficiency: Terminology, rationale and potentials* (Oeko-Institute's Working Paper 2/2013). Oeko-Institut e.V. https://www.oeko.de/oekodoc/1879/2013-007-en.pdf

Fischer, M., Foord, D., Frecè, J., Hillebrand, K., Kissling-Näf, I., Meili, R., Peskova, M., Risi, D., Schmidpeter, R., & Stucki, T. (2023). *Sustainable business*. SpringerBriefs in Business. https://doi.org/10.1007/978-3-031-25397-3

Granath, K., & Nylander, O. (2023). *MAB-Manual för analys av bostadskvaliteter*. CBA. https://www.chalmers.se/centrum/cba/mab-manual-for-analys-av-%20bostadskvaliteter/

Hedenus, F., Persson, U., & Sprei, F. (2018). *Sustainable Development - Nuances and Perspectives*. Studentlitteratur.

Jungell-Michelsson, J., & Heikkurinen, P. (2022). Sufficiency: A systematic literature review. *Ecological Economics*, *195*, 107380. https://doi.org/10.1016/j.ecolecon.2022.107380

Karman. (2021, February 10). *How to calculate how many lumens and watts are needed to illuminate a room*. https://storybox.karmanitalia.it/en/calculate-lumens-watts-illuminate-room#calculate-lumens

Ladybug Tools. (2024a). *Honeybee*. https://www.ladybug.tools/honeybee.html

Ladybug Tools. (2024b). *Ladybug*. https://www.ladybug.tools/ladybug.html

Light By Sweden. (n.d.). *Lumen*. https://lightbysweden.com/guider/lumen

Lorek, S., & Spangenberg, J. H. (2019). Sufficiency and consumer behaviour: From theory to policy. *Energy policy*, *129*, 1070–1079. https://doi.org/10.1016/j.enpol.2019.03.013

Manzano-Agugliaro, F., Montoya, F., Sabio-Ortega, A., & García-Cruz, A. (2015). Review of bioclimatic architecture strategies for achieving thermal comfort. *Renewable and Sustainable Energy Reviews*, *49*, 736–755. https://doi.org/10.1016/j.rser.2015.04.095

Meadows, D. H., Meadows, D. L., Randers, J., & Behrens III, W. (1972). *The Limits to Growth*. Universe Books. NEW YORK.

Mohamed, B., & Marzouk, M. (2025). Post-adaptive reuse evaluation of heritage buildings using multi-criteria decision-making techniques. *Journal of Building Engineerings*, *99*, 111485. https://doi.org/10.1016/j.jobe.2024.111485

Mousavinia, S. F., Pourdeihimi, S., & Madani, R. (2019). Housing layout, perceived density and social interactions in gated communities: Mediational role of territoriality. *Sustainable Cities and Society*, *51*, 101699. https://doi.org/10.1016/j.scs.2019.101699

Säwén, T. (n.d.). *Brimstone*. https://github.com/sawenchalmers/brimstone

SGBC & BRE Global. (2023). *BREEAM-SE New Construction v6.0 Technical Manual*. SGBC. https://www.sgbc.se/app/uploads/2023/05/Manual_BREEAM-SE_ENG_v6.0.2.pdf

SIS. (2011). *Hållbarhet hos byggnadsverk - Värdering av byggnaders miljöprestanda - Beräkningsmetod (SS-EN 15978:2011)*. Stockholm: SIS Förlag AB.

Sorrell, S., Gatersleben, B., & Druckman, A. (2020). The limits of energy sufficiency: A review of the evidence for rebound effects and negative spillovers from behavioural change. *Energy Research & Social Science*, *64*, 101439. https://doi.org/10.1016/j.erss.2020.101439

Spengler, L. (2016). Two types of 'enough': sufficiency as minimum and maximum. *Environmental politics*, *25*, 921–940. https://doi.org/10.1080/09644016.2016.1164355

Statistics Sweden. (2024). *Number and percentage of households by region, type of housing and size of household. Year 2012 - 2023*. https://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__HE__HE0111__HE0111A/HushallT26/

Svenskt Vatten. (n.d.). *Dricksvattenfakta*. https://www.svensktvatten.se/om-oss/verksamhet-och-strategi/fakta-om-vatten/dricksvattenfakta/

Swedish Green Building Council [SGBC]. (2022). *Miljöbyggnad 4.0 - metodik & manual ny byggnad*. https://www.sgbc.se/app/uploads/2022//12/Manual%5C_MB%5C_4.0%5C_1.pdf (Accessed: 2024-10-02).

Tröger, E. (2014). *Density and Atmosphere : On Factors Relating to Building Density in the European Citys*. ProQuest Ebook Central.

U.S. Green Building Council. (2023). *Building life-cycle impact reduction*. https://www.usgbc.org/credits/new-construction-core-and-shell-schools-new-construction-retail-new-construction-data-27?return=/credits/New%20Construction/v4.1

Vafaie, F., Remøy, H., & Gruis, V. (2023). Adaptive reuse of heritage buildings; a systematic literature review of success factors. *Habitat International*, *24*, 102926. https://doi.org/10.1016/j.habitatint.2023.102926

van Laar, B., Greco, A., Remøy, H., & Gruis, V. (2024). What matters when? – An integrative literature review on decision criteria in different stages of the adaptive reuse process. *Developments in the Built Environment*, *18*, 100439. https://doi.org/10.1016/j.dibe.2024.100439

Widström, T., & Francart, N. (2022). *Livscykelanalys av olika fasadmaterial*. KTH.

Wiprächtiger, M., Rapp, M., Hellweg, S., Shinde, R., & Haupt, M. (2022). Turning trash into treasure: An approach to the environmental assessment of waste prevention and its application to clothing and furniture in Switzerland. *Journal of Industrial Ecology*, *26*, 1389–1405. https://doi.org/10.1111/jiec.13275

Figures

Boverket. (2024b, July 3). *Introduktion till livscykelanalys (LCA)*. https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/livscykelanalys/introduktion-till-livscykelanalys-lca/

Cabeza, L. F., Bai, Q., Bertoldi, P., Kihila, J., Lucena, A., É. Mata, É., Mirasgedis, S., Novikova, A., & Saheb, Y. (2022). *Buildings*. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.011

Eriksson, L. (2024). *Efficient renewable sufficiency - a dense office transformation for resilient affordable housing* [Master's thesis, Chalmers University of Technology]. Chalmers School of Architecture. https://projects.arch.chalmers.se/wp-content/uploads/2024/06/erikssonlina_19960_3506207_Eriksson_Lina_BDTS_MT-2024-Booklet.pdf

Vogler. (2017). *Engelbrektsgatan 69*. https://commons.wikimedia.org/wiki/File:Engelbrektsgatan_69.jpg

Appendix 1

In this chapter, all calculations based on environmental product declarations and the EPD sources used are presented. Table 16 presents the owner, year, geographical region and source for the chosen EPD for each material. Table 17 presents the declared unit, the conversion factor from the declared unit to kg of material, and maintenance information along with any additional maintenance sources.

Table 16: Owner, year, region and source for each material EPD

Material	**Owner**	**Year**	**Region**	**Reference**
Gypsum plasterboard	Gyproc	2024	Nordic	Hellgren (2024)
Sawn timber	Svenskt Trä	2021	Sweden	Pantze (2021)
Stone wool	ROCKWOOL	2022	Nordic	Xanthopoulou (2022)
Wood fibre	Svenska Termoträ	2022	Sweden	Måradson (2022)
Concrete	Pilgrimstad Cementvarufabrik	2024	Sweden	Mellberg (2024)
Expanded polystyrene	IKEM/EPS Sverige	2020	Nordic	IKEM (2020)
Brick	Brukspecialisten i Sverige	2023	Sweden	Végvári (2023)
Mortar	AB Bösarps Grus & Torrbruk	2021	Sweden	Erikson (2021)
Copper Sheet	Aurubis Finland	2021	Nordic	Anttonen and Sariola (2021)
Steel	Chrisma	2024	Sweden	Borberg (2024)
Carpet	Regency Carpet	2024	Global	Forson (2024)
Linoleum	ERFMI	2019	Europe	ERFMI (2019)
Wood floor	Golvabia	2024	Europe	Lindroth (2024)

Table 17: Declared unit, conversion factor, and maintenance information for EPD materials

Material	**Unit**	**Conv. factor**	**Maintenance information**
Gypsum plasterboard	m^2	9	No maintenance required
Sawn timber	m^3	500	No maintenance required (Boverket, 2024a)
Stone wool	m^2	1.1	No maintenance required
Wood fibre	kg	1	No maintenance required (Boverket, 2024a)
Concrete	tonne	1000	No maintenance required (Boverket, 2024a)
Expanded polystyrene	m^2	1.14	No maintenance required (Boverket, 2024a)
Brick	tonne	1000	No maintenance required (Widström & Francart, 2022)
Mortar	kg	1	15 % replaced in 25 y (Widström & Francart, 2022)
Copper sheet	kg	1	No maintenance required (Boverket, 2024a)
Steel	kg	1	No maintenance required (Boverket, 2024a)
Carpet	m^2	106	Cleaned yearly + replaced every 7 years
Linoleum	m^2	3.1	Cleaned yearly + replaced every 25 years
Wood floor	m^2	7.4	Reference service life 25 years

EPD References

Anttonen, R., & Sariola, L. (2021). *Nordic Standard - Copper and copper alloys - sheet and strip for building purposes. Aurubis Finland Oy*. EPD Hub. https://www.aurubis.fi/wp-content/uploads/2023/01/EPD_Aurubis_Finland_Oy_Nordic_Standard___Antique_HUB-0258_2023-01-30.pdf

Borberg, F. (2024). *Steel Structure*. EPD International. https://www.environdec.com/library/epd13436

ERFMI. (2019). *Plain and decorative linoleum according to EN ISO 24011*. r Institut Bauen und Umwelt e.V. (IBU). https://www.environdec.com/library/epd6002

Erikson, M. (2021). *Murbruk B M 2,5*. EPD International. https://www.environdec.com/library/epd4640

Forson, S. (2024). *New Trident*. EPD International. https://www.environdec.com/library/epd5357

Hellgren, E. (2024). *Gyproc normal - standard plasterboard 12.5 mm*. EPD International. https://www.environdec.com/library/epd388

IKEM. (2020). *Eps 80 insulation board*. EPD International. https://www.environdec.com/library/epd2035

Lindroth, S. (2024). *Golvabia- Lightwood Flooring*. EPD International. https://www.environdec.com/library/epd8161

Måradson, E. (2022). *Termoträ Original & Termoträ Fire Protect*. EPD International. https://www.environdec.com/library/epd6002

Mellberg, M. (2024). *Ready mix concrete C30/37 S3 16 Bas*. EPD International. https://www.environdec.com/library/epd12238

Pantze, A. (2021). *Swedish sawn dried timber of spruce or pine*. EPD International. https://www.environdec.com/library/epd2537

Végvári, F. (2023). *REBRICK – Rödmix & Gulmix*. EPD International. https://www.environdec.com/library/epd7558

Xanthopoulou, L. (2022). *ROCKWOOL stone wool thermal insulation*. The Norwegian EPD Foundation. https://www.rockwool.com/syssiteassets/o2-rockwool/dokumentation-och-certifikat/dokumentation/epd-miljoedeklaration/epdnordicsgbi-se_v4_21_03_withfacings_annex.pdf?f=20230412100154

Appendix 2

In this chapter, the base values for the honeybee program Midrise apartment are presented for the room types Apartment and Corridor.

Apartment:

- **People:** 0.028 people/m^2
- **Lighting:** 9.4 W/m^2
- **Electrical equipment** 6.7 W/m^2
- **Service hot water:** 0.149258298958 l/m^2
- **Infiltration:** 0.000569 m^3/(s*m^2)
- **Heating setpoint:** 21.7°C
- **Cooling setpoint:** 24.4°C

Corridor:

- **People:** 0 people/m^2
- **Lighting:** 4.4 W/m^2
- **Electrical equipment** 0.0 W/m^2
- **Service hot water:** 0 l/m^2
- **Infiltration:** 0.000569 m^3/(s*m^2)
- **Heating setpoint:** 21.7°C
- **Cooling setpoint:** 24.4°C

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