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Life cycle assessment of multi-family housing designed for flexibility

A study on the climate impact of flexibility and how to account for it in a life cycle assessment

Master's thesis in Industrial Ecology

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MASTER'S THESIS ACEX30

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ABSTRACT

The Swedish society is facing a challenge of reaching important climate targets while dealing with a shortage of housing. The building sector therefore has an imperative role to play. LCA (life cycle assessment) is a valuable tool that can guide design towards sustainability. Simultaneously, housing that lasts over time and is used fully can reduce climate impacts, making design for flexibility an important strategy. However, there exists knowledge gaps on the environmental impact of flexibility along with lack of procedures to quantitatively assess architectural design strategies that are hard to measure. This thesis explores the environmental performance of design for flexibility in housing with a life cycle perspective and considers how LCA can be used to evaluate it. The process consists of; a literature review, a qualitative assessment and lastly a case study comprising an LCA of a multi-family residential building, where a flexible case enabling increased longevity and space efficiency is compared to a reference case.

The findings suggest that design for flexibility can provide essential meaning for sustainable building practice but that many benefits are scenario based. The case study reveals that a climate impact saving of 21-49 % is possible, depending on the methodological choices; functional unit, reference study period and scenarios. It is shown that commonly applied calculation methods need to be adapted to account for design for flexibility and results vary depending on it. A flexible building enables prolonging, ease of adaptations and using the long-lived parts of a building more, thus it can serve its purpose now and for a long unpredictable future.

Key words: Design for flexibility, multi-family housing, LCA, environmental assessment, climate impact, residential, sustainable architecture

Livscykelanalys av flexibla flerbostadshus

En studie i klimatpåverkan av flexibilitet samt
hur det kan medräknas i en livscykelanalys

Examensarbete inom masterprogrammet Industriell Ekologi

SANDRA MOBERG

Institutionen för arkitektur och samhällsbyggnadsteknik
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SAMMANFATTNING

Det svenska samhället står inför en utmaning att nå viktiga klimatmål samtidigt som det finns en brist på bostäder. Byggsektorn har därför en viktig roll. LCA (livscykelanalys) är ett värdefullt verktyg som kan vägleda design mot hållbarhet. Samtidigt kan bostäder som bevaras över en lång tid och används väl minska klimatpåverkan, vilket gör design för flexibilitet till en viktig strategi. Det finns emellertid kunskapsluckor om miljöpåverkan av flexibilitet tillsammans med brist på metoder för att kvantitativt bedöma designstrategier som är svåra att mäta. Denna uppsats undersöker miljöprestandan av design för flexibilitet i bostäder med ett livscykelperspektiv och överväger hur LCA kan användas för att utvärdera det. Processen består av; en litteraturstudie, en kvalitativ bedömning och slutligen en fallstudie bestående av en LCA av ett flerbostadshus, där ett flexibelt fall som möjliggör ökad livslängd och yteffektivitet jämförs med ett referensfall.

Resultaten antyder att design för flexibilitet kan vara av essentiell betydelse för att skapa hållbara byggnader men att många fördelar är beroende av scenarier. Fallstudien visar att en klimatpåverkan på 21–49% är möjlig, beroende på metodvalen; funktionell enhet, referenslivslängd och scenarier. Det visas att vanligt använda beräkningsmetoder måste anpassas för att ta hänsyn till design för flexibilitet och resultaten varierar beroende på dessa val. En flexibel byggnad möjliggör ökad livslängd, enkel anpassning och större användning av de långlivade delarna av en byggnad, således kan en byggnad tjäna sitt syfte nu och under en lång oförutsägbar framtid.

Nyckelord: Design för flexibilitet, flerfamiljshus, LCA, miljöbedömning, klimatpåverkan, bostäder, hållbar arkitektur

Contents

Preface

This master thesis of 30 ECTS is carried out as a part of the M.Sc. program Industrial Ecology at Chalmers University of Technology. It has been conducted during the fall of 2020 at the department of Architecture and Civil Engineering and the division of Building Technology.

The thesis has been conducted in cooperation with IVL, the Swedish Environmental Institute. I would thereby like to pay special thanks to Johan Holmqvist at IVL for inspiration, resources and rewarding discussions. I would also like to thank Rasmus Andersson at IVL for answering any questions I had. I would further like to give many thanks to my supervisor Alexander Hollberg for guiding me through the whole process, giving me valuable inputs and being a great support and to my examiner Holger Wallbaum for sharing his knowledge.

Lastly, I am very grateful for the endless support and encouragement from my family and friends throughout my educational years at Chalmers.

Göteborg January 2021

Sandra Moberg

Abbreviations and Definitions

A_{temp}	Heated building area
BM	LCA calculation software (Byggsektorns miljöberäkningsverktyg)
BOA	Living area
BTA	Total area
Boverket	The Swedish National Board of Housing, Building and Planning
CO_2 -eq	CO_2 equivalents
Cradle to gate	Resource extraction to finished product
Cradle to grave	Resource extraction to end of life
Dfd	Design for disassembly
Ecoinvent	LCA database
Functional unit	Measure of function and provides reference flow in LCA
GWP	Global Warming Potential
IVL	Swedish Environmental Research Institute
LCA	Life cycle assessment
OpenLCA	LCA calculation software
Reference study period	Analysis period for LCA
RoK	Rooms and kitchen

Life cycle modules

A1-A3	Product
A4	Transportation
A5	Construction
B1	Use
B2-B5	Maintenance, repair, replacement, refurbishment
B6-B7	Energy, water use
C1-C4	End of life
D	Benefits and loads

Figures and tables

Figures and tables stated without source are made by the author of this thesis.

1 Introduction

It is estimated that, for the EU, approximately half of the used energy and extracted resources comes from the construction and use of buildings (European Commission, 2014) and for Sweden one fifth of the domestic greenhouse gasses comes from the building sector (Boverket, 2020). As a consequence, Sweden has ambitious climate targets, where one is to be climate neutral by 2045 (Fossilfritt Sverige, 2018). At the same time however, the Swedish housing market is facing a shortage of housing due to urbanisation and population growth (Boverket, 2018). Further, a long-term perspective is required to generate buildings that are sustainable for a long time (Boverket, 2017; Prop. 2017/18:110) which also means that buildings need to handle shifts in the sociotechnical system, for instance from demographic and technological change (Regeringen, 2018). This means that the building sector has a central part to play if a transition towards a sustainable society is to be possible. Life cycle assessment (LCA), as an assessment tool, and design for flexibility, as a design strategy, are both commonly suggested to meet the targets of becoming climate neutral and have a sustainable building sector (Fossilfritt Sverige, 2018; Boverket, 2017; SOU, 2018).

An LCA helps to evaluate the environmental impact caused by a product, service, or process over its whole life cycle (Boverket, 2015). Because it can give a holistic understanding of a building's environmental impact, the interest for LCA as a tool is increasing and further, as of 2022, a mandatory climate declaration, including a partial LCA, will be required by Boverket (the Swedish National Board of Housing, Building and Planning) for every new multi-family residential building (Boverket, 2018). The importance of the holistic view that LCA can offer at early design stages can be reasoned by that; the development of more energy-efficient buildings has made the evaluation of all life cycle stages essential (Liljenström et al., 2014), buildings are potentially very long-lived, and buildings have a strong interrelation with environment, society and economy (Benjamin, 2017).

Architectural design strategies to lower a buildings climate impact are numerous, ranging from material to urban approaches. Studies suggest that effective ways to improve the life cycle performance can be through design strategies to reach efficient use of space, to not build at all and to extend the life of buildings (Francart et al., 2018; Gervasio & Dimova, 2018). Design for flexibility is frequently mentioned as an important design strategy to achieve just that (Boverket, 2017; Fossilfritt Sverige, 2018; International Energy Agency, 2016; Gervasio & Dimova, 2018, SOU, 2018). Therefore, it can be suggested that design for flexibility has strong implications for the building life cycle while it at the same time addresses the shortage of housing.

Design for flexibility needs to be incorporated at an early design stage, but there is a lack of procedures to assess the environmental implications of design for flexibility (Gervasio & Dimova, 2018). Studies show that there exist knowledge gaps on LCA and the linked environmental impact of many design choices (Schlanbuschet al., 2016; Watson, 2003; Malmqvist et al., 2018). Also, it is primarily specialists and engineers conducting LCAs today (Olsson et al., 2017) thus there is especially a lack of knowledge among architects and other stakeholders on the quantitative benefits of sustainable architectural design strategies that are difficult to measure.

1.1 Aim and objectives

The aim of this thesis is to explore the environmental performance of design for flexibility in multi-family housing with a life cycle perspective and to understand how LCA can be used to evaluate the design. On this foundation, the objectives are to; identify flexibility, its environmental benefits and design strategies, explore methodological choices applied in LCAs of flexible building design and related design strategies as well as in typical LCAs, and finally to assess the climate performance of flexible design. Thus, a discussion on how design for flexibility can be accounted for when assessing a building and what design strategies and parameters could potentially be big and small in terms of climate impact will be formed.

1.2 Research questions

RQ1. *What definitions, environmental benefits and design strategies of flexibility are there in relation to a life cycle perspective?*

RQ2. *What methodological choices can be made to an LCA to account for design for flexibility and how does that relate to today's typical methodological choices?*

RQ3. *What climate impact reduction can design for flexibility in multi-family housing offer according to LCA results and what parameters are most important to consider?*

1.3 Focus and Limitations

The study is limited to new multi-family housing, partly because of the climate declaration required by Boverket as of 2022 directed towards every new multi-family housing and partly because of the current housing demand. Furthermore, the study is limited to environmental sustainability and thus no research on social or economic sustainability is conducted. Also, the environmental impact to be considered in the qualitative assessment and case study is delimitated to climate change due to a general focus in the building sector on climate targets. Neither will all buildings parts be considered in the case study. Further delimitations specific to the LCA of the case study are presented in Section 6.2.1.5.

1.4 Audience

Because the topic of this thesis is not currently applied to a large extent in building practice, an audience of this thesis is the research field of LCA and building design. Furthermore, the work is directed towards architects and other stakeholders in the housing sector, as the knowledge aimed for in this thesis is meant to support making informed design decisions. Also, the work is directed to actors, working with the wider perspective, such as on the city level.

1.5 Outline of thesis

The report consists of 8 chapters. After the introduction, Chapter 2 presents a theoretical background and Chapter 3 the method of the research. Then Chapter 4 presents the result of the literature review, Chapter 5 of the qualitative assessment and Chapter 6 of the case study. Finally, Chapter 7 and 8 present the analysis and conclusions that are drawn.

2 Theory

In this chapter, a theoretical background and terms relevant and used in the report are explained.

2.1 LCA in building design

An LCA studies a product form its raw material extraction, *the cradle*, to its disposal, *the grave* (Baumann & Tillman, 2004). An LCA thereby helps to evaluate the environmental impact that is caused by a product, process or service over its whole life (Boverket, 2015).

2.1.1 Methodology of LCA

The method for carrying out an LCA is shown in Figure 1. The framework is specified further in several international standards (ISO standards) (Baumann & Tillman, 2004).

The first part is the *goal and scope definition.* This part includes a description of the context and modelling specifications. Some of the important modelling specifications to be made are:

- *functional unit*- Expresses the function of the product or system and gives a key figure that inputs and outputs can be related to and used for comparison (Baumann & Tillman, 2004).
- *System boundaries*- Specifies which processes to include, time and geographical boundaries and boundaries to other products and nature to make. An analysis period is required, which is called the *reference study period.* Because it is very hard to say how long a building will stand this is not necessarily the same as the building's *service life* (Boverket, 2020). As for the relation to other products so called *allocation methods* are required. Allocation methods are relevant when considering several life cycles and for instance reuse and recycling is dealt with. Three main allocation problems exist: multi-output, multi-input and open loop recycling (Baumann & Tillman, 2004).
- *Impact categories*- Specifies which impact categories to consider and how to present them. There exist many default lists with impact categories. Examples are climate change, acidification potential and land use (Baumann & Tillman, 2004).

The *inventory analysis* compiles the relevant inputs and outputs related to the functional unit. In the *impact assessment* the result from the inventory is translated to environmental impacts. Finally, in an *interpretation* the outcomes are interpreted relative to the goal of the study (Baumann & Tillman, 2004).

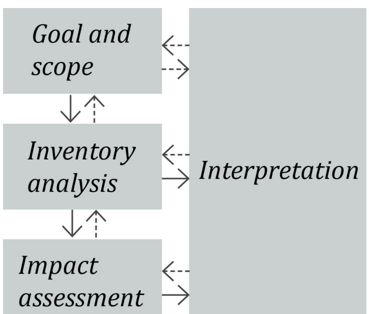


Figure 1 The framework for carrying out an LCA. Adapted from Baumann & Tillman (2004).

2.1.2 The building life cycle phases and modules

EN 15978 is a European standard that provides calculation rules for LCAs of new and existing buildings (Svenska institutet för standarder [SIS], 2011). As stated by the framework, the life cycle of a building can be divided into life cycle modules with different letter designations, see Figure 2. This can further be categorized into the phases *building*, *use*, *end of life* (and *benefits and loads*).

2.1.2.1 Building phase (module A1-A5)

The building phase is described with modules A1-A5, see Figure 2. It can furthermore be divided into a product phase, modules A1-A3 and a construction phase, modules A4-A5. The product phase (A1-A3) mainly includes raw material extraction (A1), transportation of the raw materials to manufacturing sites (A2) as well as the manufacturing of building products (A3). A1-A3 can be referred to as the cradle to gate impact (Baumann & Tillman, 2004). The construction phase (A4-A5) mainly includes transportation of products and material from the manufacturing site to the building site (A4) and the process linked to the actual completion of the building (A5) (Boverket, 2020; Liljenström et al., 2015).

2.1.2.2 Use phase (module B1-B7)

The use phase of a building is described with modules B1-B7, see Figure 2. It includes the processes related to the use (B1), interventions made in the form of maintenance, repair, replacement, refurbishment (B2-B5) as well as the operational energy and water use (B6-B7) occurring during the reference study period of the building.

Maintenance (B2) includes the planned actions needed to maintain the functional and technical performance of a building, while repair (B3) includes the unplanned actions needed as a result of for example damage. Replacement (B4) includes the planned exchange of materials, products or installations. If a building product is exchanged as part of refurbishment it should be included in B5 or if it is exchanged as the result of being damaged then it should be included in B3 (Boverket, 2020; Liljenström et al., 2015; EeBguide, 2012).

Refurbishment (B5) refers to extensive measures to a building and includes alterations of major elements or change of function or use (Boverket, 2020; Liljenström et al., 2015; EeBguide, 2012). Suggestions point to that measures taken in order to get the building back to its original standard should be included in the LCA, but a refurbishment meaning new functions should be counted for in a new LCA as the start of a new reference study period (Erlandsson & Holm, 2015; SIS, 2011).

2.1.2.3 End of life phase (module C1-C4)

The end of life phase of a building is described with modules C1-C4, see Figure 2. It includes the processes related to the building after it has reached its lifespan and no more plans for it exists. Deconstruction/demolition (C1) includes dismantling and sorting of building materials on the site. Transportation (C2) includes the transport form the site to the waste processing. Waste processing (C3) includes the processes to make the materials useable for recycle, reuse or for energy recovery. Disposal (C4) finally includes the processes related to getting rid of the material, for instance through deposit or combustion (Boverket, 2020; Liljenström et al., 2015).

2.1.2.4 Benefits and loads (module D)

The reuse, recovery and recycling potential of a building is counted in module D, see Figure 2. This makes it possible to include and quantify the benefits related to the next product system or life cycle. Module D is reported separately according to EN 15978 (Liljenström et al., 2015; Olsson et al., 2017; SIS, 2011).

Building phase					B1-B7 Use phase							C1-C4 End of life phase				D Benefits and loads
A1-A3 Product phase			A4-A5 Construction phase													
A1- Raw material supply	A2- Transport	A3- Manufacturing	A4- Transport	A5- Construction/installation	B1- Use	B2- Maintenance	B3- Repair	B4- Replacement	B5- Refurbishment	B6- Operational energy use	B7- Operational water use	C1- Deconstruction/demolition	C2-Transport	C3- Waste processing	C4- Disposal	Reuse. recovery, recycling potential

Figure 2 Life cycle phases and modules of a building as stated by the standard EN 15978. Adapted from SIS (2011).

2.1.3 Static or dynamic LCA

Because of the long lifespan of a building, changes in society and economy may have large influences on the LCA results (Su et al., 2017; Collinge et al., 2013). The most common LCA is static, but a so called dynamic LCA takes into account the changes in the sociotechnical and environmental context (Collinge et al., 2013) and thus the resulting changes in input and outputs accounted for in an LCA. According to Collinge et al. (2013) a dynamic LCA can alter the results considerably and will therefore increase the precision and usefulness of the studies. Su et al. (2017) distinguish four types of dynamic characteristics, technological progress, usage patterns, characterization factors and weighting factors.

- *Technological progress*. Technological development is rapid. Potentially with time, inputs and outputs to processes will change due to manufacturing becoming more efficient or the energy mix shifting to renewable (Su et al., 2017). This could imply dynamic inputs of for instance building performance, upstream supply chains and waste management (Eberhardt et al., 2019).
- *Usage patterns*. Dynamic inputs of use could imply considering changes in life style patterns, such as how people live and work and what preferences will look like (Su et al., 2017).
- *Characterization factors*. The impact of emissions may vary over time resulting in that the effect of outputs now is different compared to those in a future point in time. This is due to for instance background concentration of emissions (Collinge et al., 2013).

2.2 Building terms- BOA, BTA, RoK

BOA and BTA are two useful measurements of floor area used in Sweden. BOA is a measure of the living area in a building or apartment, including inner walls but excluding outer walls for instance. The term BTA measures the total area including external walls (Eringstam & Sandahl, 2018). There exist many requirements on how housing should function in Sweden, for example as laws in PBL (Plan och bygglagen) and as regulations in BBR (Boverkets Byggregler) (Eringstam & Sandahl, 2018). For instance, requirements consider basic functions, functional measurements, accessibility and separability of rooms. Number of rooms are measured by a term called RoK which stands for rooms and kitchen and is a measure of the number of rooms in an apartment excluding the kitchen. There are no requirements on specific room sizes for apartments of different RoK but apartments with different BOA have somewhat different design requirements.

2.3 Goals, targets and programs of sustainable development

In the work towards a sustainable development, international and national goals, targets and programs have been developed for the building sector, some examples are:

- *Fossil free Sweden*. In Sweden there is an ambitious national goal to have a net zero greenhouse gas emission level by 2045 (Fossilfritt Sverige, 2018). As a part of this, the construction sector has developed its own program that aims to clarify how the sector along with decisionmakers can accomplish the transition.
- *LFM30.* An example of a local program is LFM30 (Lokal färdplan Malmö 2030) developed as a way for the construction sector to cooperate (LFM30, 2019).
- *National architecture policy.* Architecture has its own goals and as of 2017 the Swedish government proposed a new national architecture policy with goals to promote good and sustainable architecture (Prop. 2017/18:110). One of the specific goals of this national architecture policy is that short-term economic profits should not be prioritized over long-term quality and sustainability.

Reports on how to reach climate goals and a sustainable built environment include many calls for action. Among them, it is commonly found calls for LCA as well as design for flexibility.

Life cycle perspective and LCA is underlined as an important tool to measure and reduce the climate impact of buildings (Boverket, 2017; Fossilfritt Sverige, 2018; LFM30, 2019; SOU, 2018). It is already implemented to some degree, but actions are being taken to increase it. For instance, LCAs are (or will be) part of several certification schemes such as BREAM, LEED, Miljöbyggnad and Svanen (Fossilfritt Sverige, 2018) and NollCO2 (NollCO2, 2020). Further, as of 2022, a climate declaration will be required for every new multi-family residential building, including a partial LCA (Boverket, 2018).

Design for flexibility is also underlined by many goals (Fossilfritt Sverige, 2018; Boverket, 2017; SOU, 2018). For example, Fossilfritt Sverige (2018) describe a visionary outlook of the building stock in the year of 2045 where:

"*Rooms can be adjusted for meetings, exhibitions, cafés, restaurants, education or accommodation*" and "*The existing residential stock and commercial premises are used significantly better and more efficiently with numerous flexible solutions where the stock is changed and refined through circular business models and refurbishments. An increased population is managed through refurbishments in addition to new production of buildings and infrastructure*" (Fossilfritt Sverige, 2018, p.13, translation made by the author).

And the national architecture policy expresses that:

" *A good design is flexible and thus has a long endurance*" (Boverket, 2017, p.13, translation made by the author).

2.4 Design for flexibility in architecture

As a background to this thesis two perspectives on flexibility are brought up. The first is the notion of the inflexible building and the second is viewing the building in layers.

2.4.1 The inflexible building- Aging and loss of value

Current apartment design is characterized by slim fit, functionally optimized apartments that are market driven and quite similar in their layout and size (Crona, 2018; Braide, 2019) one reason being an increase in prize per m^2 (Crona, 2018). At the same time, demographic changes are expected with amongst other an aging and increased population (Boverket, 2018) indicating that the functionally predefined buildings built today may not serve the required functions of the future.

Building obsolescence and loss of value often occurs as buildings age. Often, buildings are demolished because of other reasons than structural (König et al., 2010). Furthermore, buildings are often subject to being inadequately used (Francart et al., 2020). König et al. (2010) suggest that obsolescence occurs through many reasons, the main being: Functional, physical, technical, legal, economical and style. For example, functional obsolescence is when buildings no longer fulfil its purpose, and for instance many post war residential buildings are today too small for present requirements (König et al., 2010).

2.4.2 Seeing the building in layers

Stewart Brand (Brand, 1997) distinguishes six layers of a building, based on earlier work by Frank Duffy. The different layers represent different longevity and flow of change, see Figure 3. The site is the eternal layer and the stuff is the flighty layer, and everything else falls somewhere in-between. For instance, Brand (1997) deliberates on the life of the structure and how it can be equated to the life of the building. The lifespan of the structure varies, possibly between 30 and 300 years, but few buildings stand longer than for 60 years, for other explanations than that the structure has reached its full lifespan. On the contrary, the layer called space in Figure 3, representing the non-load bearing parts that form spaces and rooms, has a more volatile character, changing every 3 to 30 years according to Brand (1997).

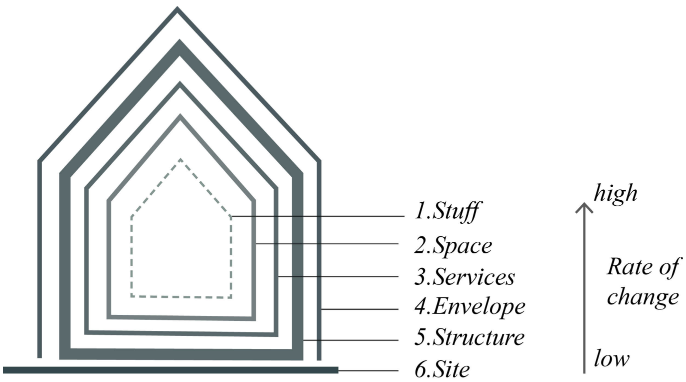


Figure 3 The layers of the building. Adapted from Brand (1997).

3 Method

In this chapter the method for carrying out this thesis is explained. Since the link between design for flexibility and LCA is a rather unexplored subject, the research methodology was chosen to enable viewing the subject from different angles. Therefore, the approach to answer the research questions was through mixed methods of both qualitative and quantitative character. Also, as described by Creswell (2014) a mixed method approach can be helpful to balance the respective strengths and shortcomings of quantitative and qualitative approaches.

The research process consisted of three main parts, a literature review, a qualitative assessment and a quantitative case study, see Figure 4. The results of the literature review were used to answer RQ1 and RQ2 (research questions 1 and 2). The results of the qualitative assessment and the case study were used mainly to explore RQ3 (research question 3), but also RQ2. The order of the process; first the literature review, then the qualitative assessment and lastly the case study was chosen as the former helped to shape and perform the latter. However, to some degree the process was of iterative character.

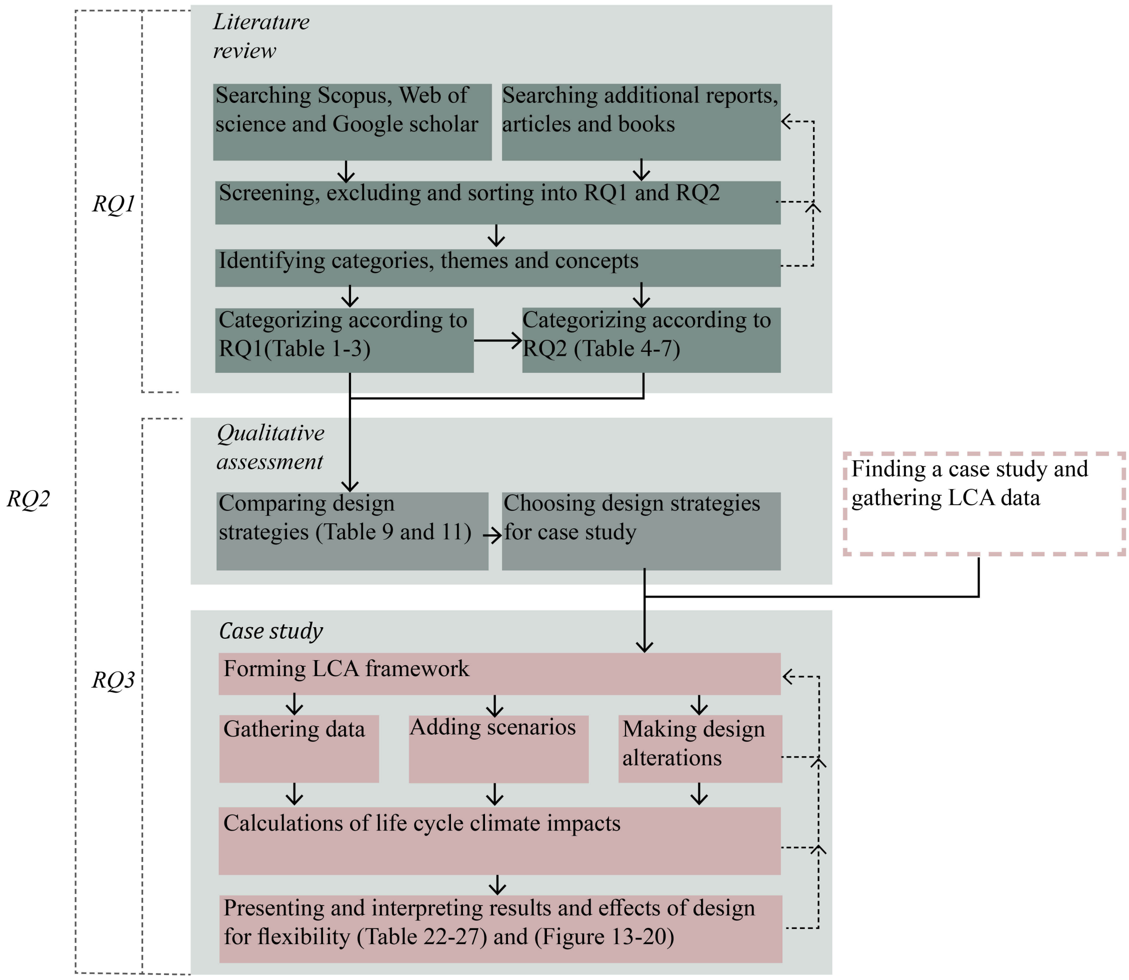


Figure 4 Research process outline.

3.1 Literature review

In order to answer RQ1 and RQ2 a literature review was made to examine LCA and design for flexibility apart and together. The review consists of literature from the databases; Web of Science, Scopus and Google Scholar as well as other relevant reports and books. Books and reports were added as a complement to the scientific literature, especially in order to answer RQ1. To some extent, the review for RQ1 helped answer RQ2 and therefore, the order of the process followed that logic. The search in databases was made using the key words: "(flexible OR flexibility OR adaptable OR adaptability AND building OR architecture OR housing)" and "(flexible OR flexibility OR adaptable OR adaptability) AND (LCA OR life cycle analysis OR life cycle assessment) AND (building)". Based on title and abstract some papers found through the databases were omitted if found to be irrelevant, such as those not focusing on buildings or on other definitions of flexibility than the scope of this thesis. Further, they were sorted into RQ1 and RQ2 (although some studies overlapped). For RQ2, primarily studies that comprised LCAs of design for flexibility and related strategies were included, but because studies on the topic were found to be scarce, studies on metrics and indicators to measure flexibility were included. When reading the studies, relevant references were continually identified and further added.

For RQ1 the following questions were explored: *1) What are the definitions of flexible design in housing? 2) What potential environmental benefits are there to design for flexibility? 3) What are common design strategies to reach flexibility?*

For RQ2 the following questions were explored: *4) What are common/recommended methodological choices for LCAs of buildings? 5) How is flexibility and related design strategies accounted for in environmental LCAs; what methodological choices are made, what parameters have a big impact and what are other significant findings?*

Afterwards, categories, themes and concepts were identified according to questions 1-5 and presented in Table 1-7.

3.2 Qualitative assessment

A qualitative assessment was conducted as a way to assess RQ2 and RQ3 in a universal way. Consequently, it was possible to explore the results from the literature and compare and contrast design strategies and climate benefits with a life cycle approach. Design strategies to include in the assessment were chosen based on how frequently they were mentioned in the literature review. The ones mentioned five or more times were regarded as common and thus chosen. The data was primarily based on findings in pre-existing LCA studies and other assessments included in the literature review. The results were then presented in Table 9 and 11.

3.3 Case study

A case study of quantitative character was chosen as a way to further answer RQ2 and RQ3. The case study consists of an LCA made on a building called Varvsporten, a multi-family residential building under development by PEAB. The calculations of the case study were based on a pre-existing calculation report for a pilot study of multi-family housing within a project financed by Vinnova and within the program LFM30, conducted in the LCA tool BM (Byggsektorns miljöberäkningsverktyg) and consisting of climate data for the life cycle modules of the building phase (A1-A5). This meant that the effort of collecting inventory data was eased.

The calculations made in the case study included additional life cycle modules and modifications to the pre-existing calculations. The study was performed with the LCA software BM version 1.0 with IVL's climate database, the LCA software OpenLCA version 1.10.3 with the data base Ecoinvent version 3.2 as well as spreadsheets.

The case study was performed by comparing the climate impacts of a reference case and a flexible case, where the reference case represented the original design of Varvsporten and the flexible case represented a modified design version of Varvsporten that enables flexibility. Assumptions and estimations of design alterations were based on the literature review as well as complementary discussions with architects. Further, methodological choices were applied to the LCA that according to findings of the literature review can credit design for flexibility. This included considering two life cycles, using several functional units and extended/several reference study periods. Because buildings are long lived, scenarios of the use and end of life phase were needed. Further, different scenarios for the reference and flexible case were created for the use phase in order to account for the potential benefits of flexibility. This included scenarios of refurbishment and longevity (modelled as two life cycles) as well as scenarios of occupancy. The potential benefits were then calculated and compared to potential drawbacks from design requirements of design for flexibility and presented in Table 22-27 and Figure 13-20.

The methodological choices made in order to perform the LCA are stated further in Section 6.2.

4 Literature review

This chapter consists of the literature review. First, design for flexibility and then LCA and its methodological choices are examined.

4.1 Design for flexibility

In this section design for flexibility in buildings is examined. Firstly, definitions of flexibility found in literature are reviewed followed by environmental benefits and design strategies. Categories and groupings are made, in order to relate flexibility to a life cycle perspective.

4.1.1 Definitions

The literature presents a rather diverse and inconsequent terminology, where adaptability and flexibility sometimes refer to similar or differing ideas. For instance, the ability to use a space differently can be defined as adaptability and the ability to change the physical organisations of a space can be defined as flexibility (Schneider & Till, 2007). However, this distinction is sometimes left out or switched in literature. For instance, Gosling et al. (2012) point out the inconsequent use of the terms flexibility and adaptability. With this in mind, flexible housing will in this thesis refer to both adaptability and flexibility to allow a wider scope of literature to be reviewed and a larger set of strategies to be put into the context of life cycle design. So, the term flexibility will be consistently used throughout this thesis even if other terms are used in literature.

The ability to accommodate, adjust to or respond to change is the key content in definitions of flexible building design, see Table 1. Schneider and Till (2007) refer to the ability to "adjust to changing needs and patterns" (p.4). Cellucci and Di Sivo (2015) add the ability of changes to be made "timely and conveniently" (p.845). The ability to adapt to the context in form of for example culture, economy and environment is also common among definitions (Cellucci & Di Sivo, 2015; Schmidt et al., 2010; Cavalliere et al., 2019).

If looking at what change refers to specifically, definitions differ a bit in scope or terminology, see Table 1. For instance, flexibility is described as a capacity to accommodate change of; space plan and structure (Gervasio & Dimova, 2018), function, technical system, loads and flow of people (Slaughter, 2001) use within the building and the volume of space in a building (Russell & Moffatt, 2001). The scope includes both changes without making physical alterations and by means of making physical alterations to the building (Schneider & Till, 2007; Schmidt et al., 2010; Cavalliere et al., 2019).

Table 1 Definitions and scope of design for flexibility within architecture according to reviewed literature.

Source	Definition of flexibility	Scope of flexibility
Schneider & Till (2007)	"Housing that can adjust to changing needs and patterns, both social and technological" (p.4)	Different social uses without making physical change and different physical designs, through temporary or permanent change to plan or construction
Russell & Moffatt (2001)	"The capacity of buildings to accommodate substantial change" (p.2)	Change of layout and additions (or subtraction) to the space in a building and changes to the use of the space
Cellucci & Di Sivo (2015)	Ability to make quick and easy changes when requirements and needs change	Change of space plan and volume, expansion and contraction, technological

		changes related to construction techniques and maintenance
Gervasio & Dimova (2018)	Accommodate changes and adapt to new functions and technique	Change of space plan and structure
Schmidt et al. (2010)	Ability to adapt quickly to a changing context and hence increasing its value	Physical change of space, services and structure and different use of a fix space
Fawcett (2011)	Accommodating unpredictable change	Ability to change use or expand/ upgrade a building
Slaughter (2001)	Ability to accommodate change	Change in function, capacity (loads or volume) and flow of environment and people
Graham (2005)	A quality that helps to ensure that a building does not become obsolete, is used as long as possible and can accommodate change with minimal resource use	Change in space, structure and material
Cavalliere et al. (2019)	Ability to adapt to changes in culture, technology, and economy	Change in structure, plan, technical services and components

4.1.2 Categories of design for flexibility

Recurring in literature is that flexibility should hold change in terms of use, function and technique. This thesis makes its own distinction of categories, based on the literature but adapted to make relevant discussions on LCA. Three main categories of flexibility are consequently distinguished for the purpose of this study, illustrated in Figure 5.

1. ***Flexibility in social use:*** Flexibility in spatial use without the need to make physical (permanent) changes to space.
2. ***Flexibility in physical use:*** Flexibility in spatial use by the means of physical changes to space.
3. ***Flexibility in material/technical use:*** Flexibility in the composition of a building by making physical changes to the material and technical components.

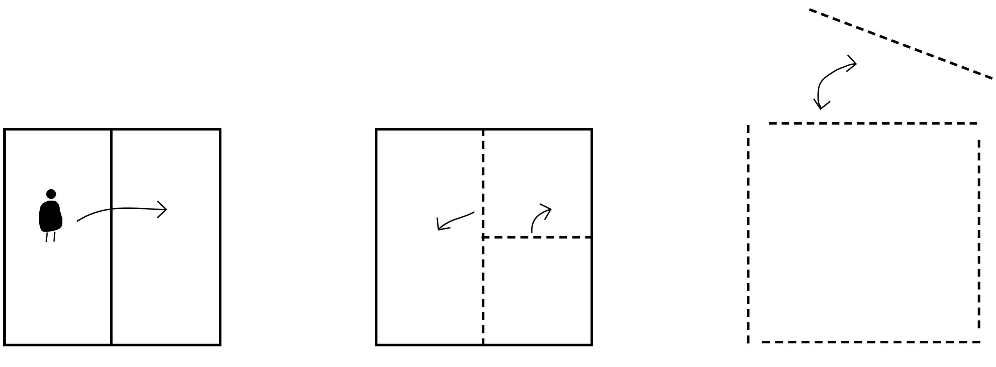


Figure 5 Flexibility in social use, physical use and material/technical use.

4.1.2.1 Category 1- Flexibility in social use

A building that is *flexible in social use* refers to the ability of it to be used differently without having to make any (permanent) physical material changes to it. If relating to the layers of a building according to Brand (1997), see Figure 3, the layer subject to change is mainly layer 1, stuff. This category is relevant when designing a building with a life cycle perspective, as it will enable flexibility without apparent need for material flows. Flexibility in social use often refers to spaces designed so they can be used in different ways, often through organisation of rooms and reduced degree of specification of room functions (Schneider & Till, 2007). Braide (2019) narrows it down to generality, which refers to spaces fixed physically but flexible in use.

For a building to be flexible in social use includes to accommodate change of occupancy or function within a defined space, on for instance a daily, annual or seasonal basis. Examples are to allow for varying number of residents to inhabit the same space (Braide, 2019), using the same space for a workplace and a playroom (Schneider & Till, 2007) or by making other uses of a school space on evenings and weekends (Francart et al., 2020).

4.1.2.2 Category 2- Flexibility in physical use

A building that is *flexible in physical use* refers to the ability of it to be used differently through the means of physical material changes to the space and plan. If relating to the layers of a building according to Brand (1997), see Figure 3, the layers subject to change is mainly layer 2, space, but also 4 and 5; envelope and structure. This category is relevant when designing a building with a life cycle perspective, as it will ensure continuity in usefulness, with as small material flows as possible. This notion of flexibility is seen broadly in literature and allows the building to change its function, use, space and size (Slaughter, 2001; Gervasio & Dimova, 2018; Schmidt et al., 2010). Another way to distinguish from *flexibility in social use*, is that *flexibility in physical use* involves more long-term changes to a building, Thus, whereas *flexibility in social use* enables temporary change and thus short-term effects, *flexibility in physical use* enables (temporarily) permanent change and thus more long-term effects.

flexibility in physical use includes changes to the floor plan, geometry or volume of a building. Examples are to divide and join together rooms (Schneider & Till, 2007) or to expand and contract spaces (Cellucci & Di Sivo, 2015).

4.1.2.3 Category 3- Flexibility in material/technical use

A building that is *flexible in material/technical use* refers to the ability to make physical change to the material and technical composition of a building. If relating to the layers of a building according to Brand (1997), see Figure 3, the layers subject to change are mainly layers 3, 4 and 5; services, envelope and structure. This category is relevant when designing a building with a life cycle perspective, as it will ease maintenance, replaceability, recovery and reuse. In contrast to *flexibility in physical use* this category touches the design of services, structure (scheme and connections) and material choice so that they can be replaced, upgraded or removed. Similarly, to *flexibility in physical use*, *flexibility in material/technical use* enables (temporarily) permanent change and thus more long-term effects to change.

flexible in material/technical use includes changes to services, structure and envelope of a building. Examples are to upgrade the ventilation system (Slaughter, 2001), install technology such as PV panels (Russell & Moffatt, 2001) and upgrade the facade (Cellucci & Di Sivo, 2015).

4.1.3 Environmental benefits

By being able to change and respond to change, both short- and long-term, flexible buildings are arguably inherently sustainable because they can provide for the present and for future generations, something that is widely accepted as inherent qualities of sustainable development (Hedenus et al., 2018). Table 2 illustrates different environmental benefits of design for flexibility as mentioned and discussed in the reviewed literature. According to the literature, the benefits can be gained over the whole life cycle on both a short- and long-term perspective. Consequently, it reveals that in order to appreciate all the benefits of flexibility, the whole life cycle of the building should be considered. Otherwise, there is a risk that strategies to achieve flexibility will be undervalued. The benefits of design for flexibility are widely discussed in literature, however, there is a lack of quantification to confirm flexibility provision and the subsequent benefits (Schneider & Till, 2005; Femenias & Geromel, 2020).

In the literature, benefits of design for flexibility are frequently described in terms of value over increased time, ease to accommodate change and multifunctionality in use of spaces. By extracting and grouping key environmental benefits from the literature, see Table 2, four categories of environmental benefit have been distinguished in relation to life cycle thinking:

- ***Extended lifespan***
- ***Decreased climate impact from maintenance, repair, replacement, refurbishment and end of life***
- ***Efficient use of space***
- ***Improved life cycle performance.***

Table 2 Environmental benefits of design for flexibility brought up in literature.

Environmental benefits of design for flexibility	Schneider & Till (2007)	Brand (1997)	Cellucci & Di Sivo (2015)	Russell & Moffatt (2001)	Gervasio & Dimova (2018)	Gosling et al. (2012)	Braide (2019)	Femenias & Geromel (2020)	Andrade & Bragança (2019)	Slaughter (2001)	Magdziak (2019)	Cavalliere et al. (2019)	Graham (2005)	Malmqvist et al. (2018)	Milwicz1& Pastawski (2018)	Francart et al. (2020)	Raviz et al. (2015)	
Extended lifespan																		21
Ability to last longer, prolonged life expectancy	×	×	×	×	×	×				×		×	×	×				
Increased value over a longer time period of time, higher appreciation	×		×				×		×	×								
Inhibition of becoming prematurely obsolete	×		×	×	×				×				×					
Decreased climate impact from maintenance, repair, replacement, refurbishment and end of life																		16
Reduced need/frequency/size of refurbishment	×			×	×	×				×								
Resilient system			×									×						
Easy maintenance			×									×						
Reduced life cycle material flows						×		×	×				×	×				

Easy and effective accommodation of change									x	x								
More efficient use of space																		11
Avoidance of lost use of buildings during maintenance, refurbishment and construction									x									
Space/material efficiency	x			x		x				x					x	x		
Reduced risk of being inadequately used	x			x														
Allowing people to stay longer in homes	x						x											
Improved life cycle performance																		4
Keeping up with technological development in an effective way, ability to accommodate new technologies	x			x		x			x									

4.1.3.1 Extended lifespan

In literature, the notion that design for flexibility can increase the lifespan of a building is rather mutual. For instance, Cellucci and Di Sivo (2015) suggest that design for flexibility can be regarded as an “antidote to obsolescence” (p.845). Graham (2005) suggests that, by designing for change, the long-lived building parts can be better sustained, because short-lived ones can be replaced. Also, according to Russell and Moffatt (2001) the ability to make changes with less effort increases the duration the building is in function. During the course of time, demands on a building will most likely change in some form, so if a building can accommodate change and is maintained well, then its life time can increase far beyond 50 years or so (Gervasio & Dimova, 2018). By extending the longevity of buildings, the replacement by new can be avoided, and the ultimate sustainable building is the one that isn’t built at all (Russell & Moffatt, 2001).

4.1.3.2 Decreased climate impact from maintenance, repair, replacement, refurbishment and end of life

Throughout the life of a building, it needs amendments to maintain, upgrade or change its performance. Also, in order to meet the needs of new users or technology, buildings are often renovated or refurbished (Slaugter, 2001; Femenias & Geromel, 2020). It can further be expected that the need for change in buildings is increasing (Gosling et al., 2012; Slaughter, 2001; Russell & Moffatt, 2001). Slaughter (2001) concludes, through an analysis of building renovation, that when buildings are renovated, they require changes to an extensive amount of building parts. For example, two thirds of the studied buildings renovated for the same use as before and 90 % of those renovated for a different use required change to the structure, suggesting that design for flexibility can decrease the subsequent issues and impacts. If design for flexibility can ease and reduce the size of actions needed along the life cycle then it can decrease material flows connected to it, both resources going in, and waste going out (Graham, 2005).

4.1.3.3 More efficient use of space

If a space is used more efficiently, then arguably, less resources will be needed. Russell and Moffatt (2001) suggest that, on average during its life time, a flexible building has potential to use less space and have a smaller footprint, as it allows the same space to be used for different activities and amount of people and also allows spaces that are unutilised to be used for something else. Magdziak (2019) similarly argues that design for flexibility means that more people can use the same space, by adapting to different family sizes or different functions. Also, Francart et al. (2020) suggest that flexible spaces can enable sharing of spaces. Slaughter (2001) furthermore adds that flexibility will reduce the loss of use that buildings come across when they are subject to change such as during renovation and maintenance.

4.1.3.4 Improved life cycle performance

Design for flexibility can make buildings more susceptible to new technologies, accommodating innovations quicker and easier (Russell & Moffatt, 2001; Schneider & Till, 2005). With climate change on the agenda, technological progress is important and it is therefore of high relevance that buildings can accommodate new technology. Gosling et al. (2012) argue that it is of importance because building regulations of for instance operational energy use are continuously changing and so in order to meet climate goals, the upgrade of existing buildings will likely be essential. Likewise, Slaughter (2001) and Russell and Moffatt (2001) suggest that the need for change is increasing as technological development is accelerating.

4.1.4 Design strategies

Design for flexibility can be achieved through a wide range of strategies, as found in literature and depicted by Table 3. For the sake of this thesis, they are grouped according to what parameter the design strategy addresses and which of the three defined categories of design for flexibility they address, see Figure 5. Some address *geometry and plan* to enable *flexibility in social* and *physical use* and some address *material and services* to enable *flexibility in physical* and *material/technical use*. Noted should be that several design strategies overlap and could potentially mean similar things depending on perception. Also, often several design strategies are combined in practice. Those that have been found most frequently in the literature (five times and more) are described further in Section 4.1.4.1 and 4.1.4.2.

Table 3 Strategies of design for flexibility according to literature.

Design strategies	Schneider & Till (2007)	Brand (1997)	Cellucci & Di Sivo (2015)	Russell & Moffatt (2001)	Gervasio & Dimova (2018)	Gosling et al. (2012)	Braide (2019)	Femenias & Geromel (2020)	Andrade & Bragança (2019)	Slaughter (2001)	Magdziak (2019)	Cavalliere et al. (2019)	Graham (2005)	Malmqvist et al. (2018)	Milwicz1& Pastawski (2018)	Geraedts et al. (2014)	Živković & Jovanović (2012)	Raviz et al. (2015)	
Geometry and plan																			
Shared spaces	×						×												2
Increased size of circulation/communication space (private and public)	×																		1
Sliding/movable walls (with efficient space plan)	×		×				×				×	×						×	6
Foldable furniture (with efficient space plan)	×		×				×				×	×						×	6
Functionally neutral rooms	×	×	×	×		×	×	×				×	×					×	10
Undecided or soft space (indicative)	×		×			×													3
Geometrical regularity of plan		×					×	×				×				×	×		6
Potential for expansions/contractions (vertical and horizontal)	×		×				×				×								4
Placement of service core	×							×		×		×				×	×		6
Regular grid			×									×	×			×			4
Large structural spans				×	×														2
Loose fit instead of tight fit floor plans	×			×				×								×	×		5
Increased floor height				×	×	×							×		×				5
Amount/ placement of windows and entrances												×					×		2
Non load-bearing inner walls	×	×			×				×			×			×		×		7
Demountable interior walls				×				×			×			×		×			5
Clear structural spans	×																		1
Material and services																			
Structural redundancy access	×				×	×			×	×			×						6
Design for disassembly	×	×	×		×	×			×	×		×	×	×		×			11

Flexibility in social use

Flexibility in physical use

Separate/ separable construction layers	X	X				X				X			X		X	X			6
Straightforwardness and readability in construction	X																		1
Interchangeable subsystems and components			X		X	X			X	X		X	X			X			8
Accessible subsystems and components						X			X	X			X			X			5
Zoned subsystems and components						X				X									2

4.1.4.1 Geometry and plan

Strategies addressing *geometry and plan* enable, as defined in this thesis, *flexibility in social use*, *physical use* or both, see Table 3.

According to the literature, the most contemplated strategies to achieve *flexibility in social use* is through *movable walls*, *foldable furniture* and *functionally neutral rooms*. *Movable walls* and *foldable furniture* are effective ways to quickly change the use of a space, especially for small spaces (Cellucci & Di Sivo, 2015), which in turn can enable more efficient use of space (Magdziak, 2019).

Designing *functionally neutral rooms* is a strategy that is based on getting rid of room labels, through designing neutrally sized rooms (Cellucci & Di Sivo, 2015; Schneider & Till, 2005). By eliminating the hierarchal order and unambiguously specific use of rooms, they can be used in not just one, but in several ways by a variety of constellations and number of people. This design strategy often means increasing the size of some rooms (such as bedrooms) and decreasing the size of others (mainly the living room). Good general room dimensions are according to Schneider and Till (2005) 3.2 x 3.8 meters and according to Eringstam and Sandahl (2018) 3.6 x 3.6. *Functionally neutral rooms* allows flexibility in both *social use* (as it doesn't require physical change) but also in *physical use*, since it opens up to a variety of design constellations. Consequently, it has also been argued that more efficient use of space is achieved across time (Schneider & Till, 2005; Živković & Jovanović, 2012). *Functionally neutral rooms* overlaps with designing for *"loose fit" instead of "tight fit*". Schneider and Till (2005) argue that the slim fit design often seen today, means that housing is seen as a consumer product that results in obsolescence built-in form the very start. As a general room often is square shaped (Živković & Jovanović, 2012), this strategy also overlaps with *geometrical regularity of plan*.

Increased floor height is a strategy to for instance not limit the use of a building to housing. Regulations on minimum floor height are different depending on the use and for housing it is smaller than for commercial use (Graham, 2005). This means that generally it is easier to change a public space to residential than the other way around.

The *placement of the service core* is another commonly advised strategy in literature. The service core can include bathrooms, kitchen and even wardrobes and the idea is to gather the elements that are most static in one suitable place (Živković & Jovanović, 2012). According to Živković and Jovanović (2012) a central position creates most flexibility.

Non load bearing inner walls (or *demountable walls)* is about designing the space (and construction) in a way that minimizes internal loads, in order to be able to take away or add walls (Gervasio & Dimova, 2018). On the simplest term, this refers to the walls within an apartment. Schneider and Till (2005) also describe it in terms of *clear structural spans* which refers to no load bearing walls across the width of a building.

4.1.4.2 Material and services

Strategies addressing *materials and services* of a building enables, as defined in this thesis, *flexibility in physical use*, in *material/technical use* or both.

Structural redundancy is a way to future proof a building by making sure it can accommodate different uses and loads, which can be done by slight over dimensioning of structural elements (Graham, 2005; Gervasio & Dimova, 2018).

Design for disassembly is a rather wide concept and refers to the ability to deconstruct building elements, layers and materials (Graham, 2005). Examples can be an adjustable facade and using dry or mechanical connections (Cellucci & Di Sivo, 2015). It can be achieved by designing s*eparate/ separable construction layers* (Graham, 2005) and therefore these strategies often go hand in hand.

Many design strategies for flexibility concern subsystems or components, especially referring to *interchangeability* and *accessibility* of them. This sometimes overlaps with *design for disassembly* but often refers to the location and design of service installations. Interchangeable and accessible services create flexibility by enabling and reducing the effort needed to upgrade and change functions along with new requirements (Cellucci & Di Sivo, 2015; Slaughter, 2001). According to Schneider and Till (2005) upgrading and replacing services can come with very high costs and it is not uncommon for buildings to be torn down because of the reason that services and installations have become obsolete.

4.1.5 Summary of the section

To conclude, many ideas of design for flexibility seem to revolve around finding a balance between preservation and alteration. Graham (2005) suggests that design for flexibility enables preserving what we value by minimizing alterations. Schmidt et al. (2010) suggest that the change is in the context and that good architecture will continue to exist and mature within this dynamic setting. In doing so, the goal of design for flexibility is perhaps as Leupen (2006) describes it that by designing for change the goal is durability and permeance and not change in itself.

4.2 LCA and methodological choices

This section presents the part of the literature review that examines LCA of design for flexibility. As existing LCAs on flexible buildings are limited, the scope includes related design strategies and assessments in general. Since flexibility in this thesis refers to a rather inclusive range of strategies, see Table 3, LCAs of design for disassembly (dfd), space sharing, lifespan, renovation and refurbishment are included. This section first looks into typical or recommended methodological choices of LCAs. Then methodological choices of LCAs assessing design for flexible and related design strategies as well as indicators and metrics to measure and assess the degree of flexibility are examined. Furthermore, significant results from LCAs are summarized and reviewed.

4.2.1 Recommended methodological choices

In order to discuss potential methodological choices of LCAs to account for design for flexibility, it is relevant to compare and contrast to typical methodological choices. For this, suggested methodological choices for the LCAs of the climate declarations (required by Boverket for every new multi-family residential building as of 2022) and the certification system NollCO2 are chosen as applicable for Swedish housing, see Table 4. NollCO2 is a certification system aimed to achieve net zero climate impact of buildings (NollCO2, 2020) and is thus one of the tougher certification systems in Sweden. As can be seen from Table 4, the functional unit to report results against is *m^2 BTA* for both, but the other methodologic choices differ a bit. According to Boverket (2018), the intention with the climate declaration is to start with including the building phase (modules A1-A5) but to eventually include all modules according to the standard EN 15978, see Figure 2. For the certification NollCO2 however, all life cycle modules that are considered to be substantial for the accuracy of the result are included, expect for module D (NollCO2, 2020). The only recommended allocation method found is for NollCO2, where building with reused materials should be burdened only with transport and processing (NollCO2, 2020). No method to benefit design that beds for reuse is found.

Table 4 Recommended methodological choices of LCAs.

Source	**Topic**	**Included building parts**	**Functional unit**	**Included life cycle modules**	**Reference study period (years)**	**Allocation method**
Boverket (2018)	Report with suggestions of methods for the building climate declarations	Building envelope, load bearing structure, non-load bearing inner walls	m^2 BTA	Initially A1-A5, then all		
NollCO2 (2020)	Manual with methods for calculating the climate impact according to the certification system NollCO2	Load bearing structure, foundation, building envelope, inner room forming parts, interior surfaces, services (incomplete and simplified list)	m^2 BTA	A1-A5, B4-B7, C1-C4	50	Reused materials are burdened with transportation and processing and included in module A1-A3

4.2.2 Methodological choices of LCAs accounting for design for flexibility and related design strategies

Table 5 illustrates methodological choices applied (or discussed) for LCAs of design for flexibility and related strategies.

4.2.2.1 General findings

Firstly, from the literature it is clear that methodological choices vary quit a lot. Even though this allows tailoring the assessment and answering specific questions it introduces some difficulties. The diversity of methodological choices not only introduces an element of ambiguity when conducting LCAs but also influences results and makes it hard to, with separate cases, determine what strategies have best potential to reduce the climate impact (Malmqvist et al., 2018; Eberhardt et al., 2019).

From the literature it can be further concluded that there is a lack of LCA studies on a variety of sustainable design strategies. In the literature, it is deliberated that there is an absence of quantifications made on the environmental and economic benefits of design for flexibility as well as of flexibility provision in itself is (Schneider & Till, 2005; Femenias & Geromel, 2019, Estaji, 2017). Malmqvist et al. (2018) conclude that few studies exist that assess the built-in climate impact from design strategies such as flexibility and material reuse, but that studies commonly assess choice of construction materials such as wood as oppose to concrete. Andrade and Bragança (2019) state that even though building sustainability standards to some extent recommend addressing flexibility in sustainability assessments, such as ISO 21929-1:2011 and EN 16309:2014, it is not given large focus, especially not in early design stages.

The need to include scenarios when assessing design strategies such as flexibility is brought up by several authors (Gervasio & Dimova, 2018; Dodd et al., 2017). There are uncertainties and difficulties to scenarios and several raise the concern that it is difficult to handle scenarios and the unknown future of buildings. Malmqvist et al. (2018) and Lowres and Hobbs (2017) claim that there is no unified strategy nor guideline to work with scenarios of the use and end of life phases and Rasmussen et al. (2020) that the results are very sensitive to the choice of scenarios.

4.2.2.2 Functional unit

The choice of functional unit varies in the literature to some extent, see Table 5. The most common is *m^2 BTA and year*. However, occupancy based as oppose to area-based metrics and measuring the whole building is also present (Francart et al., 2020; Bastos et al., 2014; Minunno, et al., 2020). Francart et al. (2020) discuss operational energy performance metrics (including functional units) and different ways to normalise values than with floor area, where *per person* and *floor area and time of use* are found to be two possible ways. Bastos et al. (2014) study the effect of the functional unit when comparing the environmental impact of housing of different size but the same occupancy, when using the functional unit *area and year* compared to *inhabitant and year*. The motive for using functional units that are occupancy based instead of area based is that it can benefit or credit strategies for more efficient use of space (Francart et al., 2020; Bastos et al., 2014). Furthermore, paradoxically, area based functional units could mean that the bigger the building is the lower the impact could be (per m^2) (Bastos et al., 2014).

4.2.2.3 Life cycle modules

Which life cycle modules to include is another methodological choice that varies, see Table 5. All assessments include the production phase, modules A1-A3. However, all LCAs that assess design strategies related to flexibility also include modules of the use and end of life phase. This can be justified by the fact that design for flexibility gives benefits along the life cycle, see Table 2. Which modules of the use phase to include varies depending on the specific question of the study. For instance, Eberhardt et al. (2019) only include replacement, B4 as this is a module that design for disassembly affects. Rasmussen et al. (2020) also include refurbishment, B5 to assess how flexible design strategies affect extensive building alterations. In order to account for benefits from reusing and recycling, module D is also included (Eberhardt et al., 2019; Minunno et al., 2020; Marsh, 2017; Tingley & Davison, 2012).

4.2.2.4 Reference study period

The chosen reference study period varies between 50 and 120 years, see Table 5. Building lifespan is brought up as an important aspect of LCA (Marsh, 2017; Itard & Klunder, 2007; Eberhardt et al., 2019) although the reference study period often is chosen without considering it (Marsh, 2017). For instance, Marsh (2017) suggests that when distinct designs of a building are studied, lifespan and reference study period should be contemplated as oppose to choosing the reference study period arbitrarily. Marsh (2017) also discusses the weight of the reference study period for the reason that LCA impact results often are normalized per year to study the different life cycle phases in contrast to each other. Furthermore, lifespan also becomes relevant when considering the number of material replacement needed over a building's life, as the environmental impact will depend on the relation between the component and building lifespans (Eberhardt et al., 2019; Itard & Klunder, 2007). Yet, even though the lifespan of the building plays an important role in LCAs it is often not given large focus (Marsh, 2017).

4.2.2.5 Allocation method

For studies considering subsequent systems, by for example including reuse, the allocation method between the systems becomes relevant. Eberhardt et al. (2019) and Minunno et al. (2020) calculate the benefits from building with reusable and recyclable materials as prevented impacts, from not having to produce new material, in module D. Eberhardt et al. (2019) furthermore include multiple building life cycles and divide the burdens and benefits from reusable parts between the number of cycles. Similarly, Tingley and Davison (2012) recommend that the environmental impact of reused/reusable materials is split between the number of life cycles. Collins (2010) follows the cut off approach to allocate benefits from reuse. The cut off approach is an allocation method to handle so called open loop recycling, where each cycle is responsible for the impact directly caused by that cycle (Baumann & Tillman, 2004).

How to include refurbishment encompassing new or upgraded functions is a bit ambiguous. According to EN 15978 (see Section 2.1.2.2), it should preferably count as a new life cycle (and thus a new LCA) (Erlandsson & Holm, 2015; SIS, 2011). However, Rasmussen et al. (2020) include an extensive refurbishment with building extensions and changed floor plan as a part of the current life cycle.

Table 5 Methodological choices of LCAs or discussion of LCAs made to assess flexible design and related strategies.

Source	Method and topic	Included building parts	Functional unit	Included life cycle modules	Reference study period (years)	Allocation method if relevant
Eberhardt et al. (2019)	LCA, dfd	All related to construction, services	m^2 BTA and year	A1-A3, B4, C3-C4, D	50 and 80	Benefits are included in module D and impacts are split equally between life cycles
Rasmussen et al. (2020)	LCA, flexibility, dfd, low maintenance	All related to construction	m^2 BTA and year	A1–A3, B4, B5, C3-C4	120	

Francart et al. (2020)	Literature review and interview, Sharing space, operational energy		E.g. energy use per person and energy per floor area and time of use			
Minunno et al. (2020)	LCA, Circular strategies (dfd and reuse)		The whole building	A1, A3, B2-B5, C1, C3-C4, D		Benefits are included in module D
Marsh (2017)	LCA, lifespan	External and interior walls, roof, foundation, floors	m^2 of each building component and year	A1- A4, B2-B3, B5, C1-C4, D	50, 80, 100 and 120	
Itard & Klunder (2007)	LCA, maintenance, insulation measures, refurbishment and rebuilding		m^2 BTA and year		90 and 100	
Bastos et al. (2014)	LCA, space efficiency	External and interior walls, floors, staircases roof, windows, doors	m^2 and year and inhabitant and year	Construction, refurbishment and operational energy use	75	
Collins (2010)	LCA, flexibility, energy consumption insulation material				60	Cut off approach: Only the direct burdens are allocated to each cycle
Tingley & Davison (2012)	Discussion on LCA methodology, Dfd, reuse		m^2 BTA and year	A1-A5, B2-B3, B5-B7, C1, D		Total impact, except for the use phase, is divided between the number of life cycles

4.2.3 Indicators and metrics to measure and assess flexibility

As already indicated, quantitative assessments of flexibility are rather scare, both when it comes to assessing the environmental performance as well as the flexibility provision in itself. Therefore, studies on indicators and metrics to measure design for flexibility are reviewed, see Table 6. Andrade and Bragança (2019) and Cavalliere et al. (2019) propose ways to measure the degree of flexibility in buildings as a part of the early design processes. Gervasio and Dimova (2018) propose adding a flexibility index to the functional unit of an LCA as a way to credit the employed design strategies. Dodd et al. (2017) further discuss, as a part of a common EU framework, ways to make scenarios to assess flexibility of residential and office buildings. What they have in common is the goal that, by developing strategies to evaluate design for flexibility, it can be identified, measured and also valued.

Table 6 Proposed and discussed indicators/ metrics to measure and assess design for flexibility.

Source	Proposed/discussed flexibility indicator/metric
Gervasio & Dimova (2018)	Flexibility index added to the functional unit: (m^2 and year)/ flexibility index
Andrade & Bragança (2019)	Two indicators: flexibility provision (assesses the design strategies) and flexibility area (measures the flexible area)
Dodd et al. (2017)	Guidance on making scenarios of lifespan, flexibility performance and end of life as well as indicators to measure the flexibility provision
Cavalliere et al. (2019)	Design criteria are converted into mathematical expressions to measure the flexibility provision

4.2.4 Significant results from LCAs

Significant results from reviewed LCAs are summarized in Table 7 in order to get an understanding of what has potential for large climate impact reduction (for instance which building parts or design strategies) and to assess why results differ quite a bit, see Table 7. For methodological choices of respective study, see Table 5.

Eberhardt et al. (2019) make a comparative LCA of an office building designed for disassembly and a traditional reference case. The study discovers that the concrete components with long lifespans, especially the floors, have the largest impact, but also for instance the inner walls are of importance. The study concludes that more use cycles and extended lifespan of the building is very beneficial, and together with material choices these are among the most important building parameters for lowering the climate impact, as it means a delay of producing raw materials. Reusing the concrete structure two and three times with a reference study period of 50 years for each cycle, results in 18 and 25% climate reduction. The study takes into account that not all concrete will be reused more than once and that only the internal parts are suitable for reuse, which is why these numbers don't diverge more.

Rasmussen et al. (2020) make a comparative LCA of a reference house and several different low carbon design strategies where one is a house designed for flexibility. The flexible house is designed for disassembly and the LCA includes a refurbishment with a remodel of interior walls and an extension of the house. What is interestingly found is that the flexible house does not have a notably higher impact than the reference house from the building phase (module A1-A5). The refurbishment of the flexible house has a climate impact that is 47% lower, which results in a 17 % gain over the whole life cycle.

Minunno et al. (2020) make a comparative LCA of a building designed for circularity, mainly through design for disassembly and reuse, and a traditional reference building. The circular building gets a lower impact in the building phase from the reused materials, in refurbishment (module B5) from requiring less material and also gets benefits in module D because materials can be reused. For the reference building, materials are sent to recycling or disposal at the end of life. The circular building has a climate impact that is 88% less than the reference building. When only considering design for disassembly and not reuse in the building phase, the impact reduction decreases to approximately 50%. Minunno et al. (2020) also make a comparison between reuse and recycle at the end of life phase, where the result shows that reuse compared to recycle allows a climate impact saving of 37%.

Minunno et al. (2020) considers reuse and design for disassembly in the life cycle modules A, B and D which could be an explanation why the climate impact reduction is comparatively large for this study, while for instance Rasmussen et al. (2020) only consider benefits from refurbishment. Eberhardt et al. (2019) split the benefits of reuse between the life cycles while Minunno et al. (2020) allocate all benefits to the first cycle. This also means that Eberhardt et al. (2019) directly merits the number of reuse cycles while Minunno et al. (2020) does not. Differences could also be explained by different assumed degree of disassembly potential, methodological choices and calculation procedures.

Marsh (2017) makes an LCA of building components and tests the effect of extending the lifespan of the building. The study notes the importance of the lifespan of building components in comparison to the lifespan of the whole building. For instance, if a component has a longer lifespan than the chosen reference study period of the building, the impact of that component normalized per year will be larger the shorter the reference study period is. The mean value of doubling the lifespan from 50 to 100 years results in a 38 % climate impact reduction. The study concludes that it is worth designing for long building lifespans and that an important way to reach this is to design the building for flexibility.

Itard and Klunder (2007) make an LCA of two post war multi-residential buildings for four scenarios: maintenance, insulation upgrade, refurbishment and demolition/rebuilding. The buildings are located in areas planned to be demolished and rebuilt with new floor plan designs but because the design of the existing buildings allows for it, refurbishment is in the study considered as an alternative (as the loadbearing structure and floor plan does do not hinder new functions and layouts). The refurbishment is hypothetically made by for instance joining together apartments and adding storeys. What is found is that refurbishment has a considerably lower climate impact than demolition/rebuilding, with 60 % less embodied materials. The floors, foundation, inner walls and facade contribute the most to the impact. Further, the amount of demolition waste is considerably less for refurbishment, on average 15 % of demolition/rebuilding. It is also concluded that transformation must be feasible and that the building therefore has to be designed with flexibility in mind.

Bastos et al. (2014) make a comparative LCA of three similar residential houses with different sizes but the same occupancy. By changing the functional unit, it is concluded that larger buildings have a lower climate impact when assessed per m^2 and smaller buildings have a lower impact when assessed per person.

Due to applying the cut off approach (see Section 4.2.2.5) a study by Collins et al. (2010) find that designing for future reusability has a lower energy saving in the LCA than designing with reused parts (12% on average compared to 36%).

Table 7 Life cycle climate impact (kg CO_2-eq) reduction of design strategies.

Source	**Type of building/ object assessed**	**Design strategy**	**Life cycle climate impact reduction**
Eberhardt et al. (2019)	Office	Dfd: reuse of concrete structure two times (lifespan 50 years) compared to a traditional reference case and the variety caused by different scenarios of building composition	18 % (18-49 % depending on composition)
Rasmussen et al. (2020)	Single residential	Design for flexibility: refurbishment compared to a traditional reference case	17%
Minunno et al. (2020)	Office	Circular strategies (dfd and reuse) compared to a traditional reference case Reuse vs recycling	88% 37%
Marsh (2017)	Building components	Lifespan of 80, 100 and 120 years relative to 50 years for a mean value of all building components	29% 38% and 43% (mean value of seven impact categories)

Itard & Klunder (2007)	Multi residential	Refurbishment vs demolition and rebuilding	60% (material)
Bastos et al. (2014)	Multi residential	Different apartment sizes, same occupancy: effect of changing functional unit from *person and year* to *m^2 and year* for the larger house	9-11%
Collins et al. (2010)	Insulation material	Flexibility, with focus on energy consumption: building with new parts that are reused after demolition and building with reused parts that are disposed after demolition	12% and 36% (energy)

4.2.5 How to account for and credit design for flexibility in an LCA

The studies included in the literature review give an indication of how an LCA can account for design for flexibility and thus evaluate its potential climate benefits. A mix of methodological choices can be allowed, as shown by reviewed LCAs. Important to have in mind however, is to not double count benefits and impacts, which for example Eberhardt et al. (2019) discuss concerning allocation of benefits. Indicated by the studies is also that suitable methodological choices can vary depending on the specific design strategy implemented. Methodological choices that are found to enable accounting for flexibility are illustrated in Figure 6.

Eberhardt et al. (2019) argue that in order to support design for circularity, LCA needs to consider *multiple life cycles* as oppose to one life cycle. Arguably, this could support design for flexibility, as flexibility enables increased longevity and new functions, the latter which according to Erlandsson and Holm (2015) preferably should count as a new life cycle.

Another way to credit the benefits of increased longevity seems to be through *extended reference study period*. Marsh (2017) reflects on that longer reference study periods (than 50 years or so) perhaps should be used or considered to give a more accurate assessment, since housing often has potentially longer lifespans.

Rasmussen et al. (2020) don't consider multiple life cycles in the LCA, but include an extensive refurbishment involving a new floor plan, within one life cycle, which reference study period is set to 120 years. To *include refurbishment encompassing new and/or upgraded functions* could thus possibly be another way for an LCA to account for design for flexibility, then perhaps combined with a longer reference study period. An issue could be if the functional unit changes with a refurbishment and how to handle that (Erlandsson & Holm, 2015).

Eberhardt et al. (2019) and Minunno et al. (2020) include the benefits from future reuse in life cycle module D. Because design for flexibility often enables reuse of building components or whole buildings, *including the benefits from reuse in module D* could be another way to account for the design strategies in an LCA.

Making more than one scenario can give an idea of how big (and little) effect design strategies can have (Eberhardt et al., 2019; Marsh, 2017; Itard & Klunder, 2007) while reducing the uncertainties of scenarios (Dodd et al., 2017).

Finally, by using several functional units, benefits such as space efficiency can be accounted for in an LCA (Francart et al., 2020; Bastos et al., 2014). Using *an occupancy as well as an area based functional unit* could therefore be a way to credit design for flexibility.

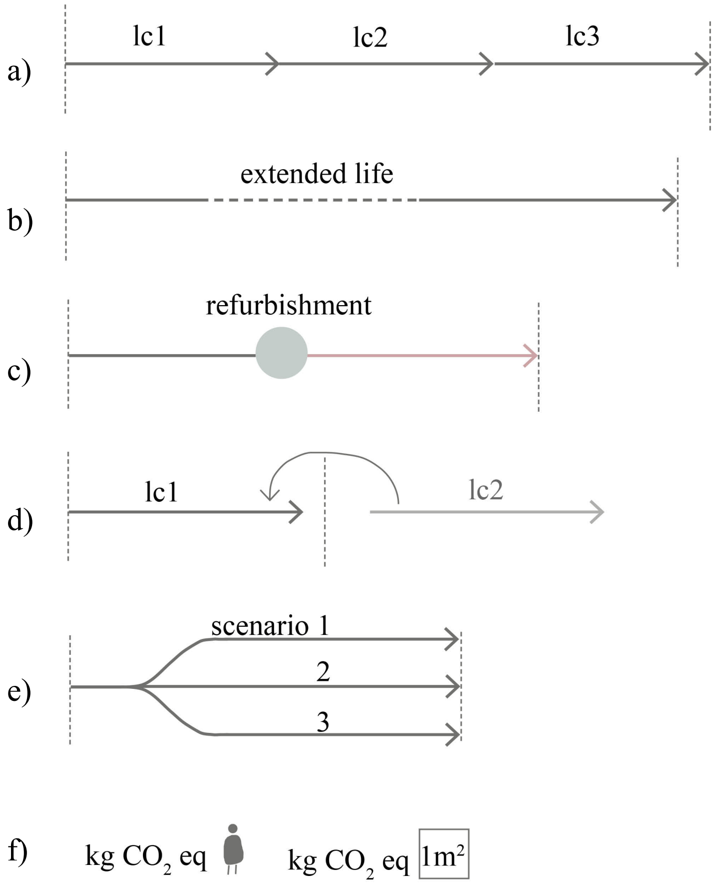


Figure 6 *Possible LCA methodologies to account for and credit design for flexibility: a) multiple life cycles, b) extended reference study period, c) include refurbishment encompassing new and/or upgraded functions, d) include the benefits from reuse in module D, e) make more than one scenario, f) an occupancy as well as an area based functional unit. lc-life cycle. The vertical dashed lines are the system boundaries for the studied system.*

5 Qualitative assessment of design strategies for flexibility

This chapter evaluates the climate impact of design for flexibility from a life cycle perspective. It is done through a qualitative assessment of chosen design strategies and is based on the literature review.

5.1 Introduction- Design strategies

The design strategies that are assessed represent all three categories of design for flexibility defined by this thesis, see Figure 5, and are chosen as they are mentioned regularly in literature, see Table 3. The ones mentioned five or more times were regarded as common strategies and are thus assessed. Important to distinguish however, is that even though these design strategies are mentioned regularly in literature, it does not necessarily mean that they are most frequently applied in building design. The design strategies are further described in Section 4.1.4.

5.2 Framework

The goal of the qualitative assessment is to give an overview and indication of where benefits and impacts can occur along the building life cycle. It does this by looking at several design strategies for flexibility and their climate impact over the building life cycle. It does not follow an LCA framework as described in Section 2.1.1, but some methodological choices are applied which are described below.

5.2.1 Methodological choices

The life cycle modules B1, B3 and B7 are excluded from the study. This can be justified by that the literature review, see Table 5, points to lack of relevance of these modules in regards to design for flexibility. Another reason why B3 is not included is because it is hard to evaluate when repair might be needed (Liljenström et al., 2015). Additionally, NollCO2 (2020) makes the judgement that B1 and B3 can be excluded because of small impacts compared to the other modules.

The reference study period is approximately 50 years as this is a common period, see Table 4 and 5. However, the studies that the assessment partially is based on uses a diversity of reference study periods, see Table 5, and therefore, the time period is not meant to be in focus. In order to incorporate design for flexibility however, an extended reference study period and multiple life cycles are considered beyond this time period. This also means that extensive refurbishment is considered, which according to Erlandsson and Holm (2015), can be expected for a longer lifespan then 50 years.

A distinction can be made between reusing a building or reusing building parts at the end of a life cycle. Therefore, extended lifespan or multiple lifecycles of the building is distinguished from multiple life cycles of components.

5.2.2 Data collection

As previously mentioned, quantitative assessments of design for flexibility are scarce. Therefore, a mix of quantitative and qualitative valuations in literature is utilized, and when lack of either, assumptions made by the author are made. From the literature with qualitative statements, conclusions of both direct and indirect statements have been drawn. Table 8 shows the colours used to indicate the type of data used. The compilation of data that the qualitative assessment is based on is described in Table 9.

Table 8 Colours used to indicate type of data.

Quantitative assessment from literature	■ (dark)
Qualitative assessment/statement from literature (direct or indirect)	■ (medium)
Assumption made by the author	■ (light)

Table 9 Life cycle impacts of chosen design strategies from quantitative and qualitative studies of the literature review.

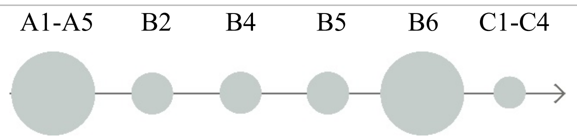
Design strategy (see Section 4.1.4)	Environmental benefits (see Section 4.1.3)	Life cycle module where increase is possible	Life cycle module where reduction potential is possible
Functionally neutral rooms ***or*** ***Loose fit instead of tight fit floor plans***	More efficient use of space (during life cycle): Russell & Moffatt (2001), Magdziak (2019) Extended lifespan: Schneider & Till (2007), Cellucci & Di Sivo (2015), Russell & Moffatt (2001) Less impact from use and end of life phase: Slaughter (2001), Russell & Moffatt (2001), Femenias & Geromel (2019)	A1-A5: although depending on functional unit (Bastos et al., 2014) ■ (dark) B4: similar to A (Bastos et al., 2014) ■ (dark) B6: similar to A (Bastos et al., 2014) ■ (dark)	B5: Itard & Klunder (2007) ■ (dark) B6: If more efficient use of space (Russell & Moffatt, 2001; Magdziak, 2019) ■ (medium) D: Extended lifespan ■ (medium)
Sliding/movable walls and foldable furniture	More efficient use of space: Schneider & Till (2007)	B2, B4 ■ (light)	A1-A5: Bastos et al. (2014), Russell & Moffatt (2001) ■ (dark) B6: Bastos et al. (2014) ■ (dark)
Placement of service core	Extended lifespan: Schneider & Till (2007) Less impact from use and end of life phase: Schneider & Till (2007)		B5: Less impact from use and end of life phase. ■ (medium) D: Extended lifespan ■ (medium)
Geometrical regularity of plan	Extended lifespan: Schneider & Till (2007) Less impact from use and end of life phase: Femenias & Geromel (2019)		B5: Less impact from use and end of life phase. ■ (medium) D: Increased longevity ■ (medium)
Increased floor height	Extended lifespan: Graham (2005)	A1-A5 ■ (light)	D: Extended lifespan ■ (medium)
Structural redundancy access	Extended lifespan: Schneider & Till (2007)	A1-A5 ■ (light)	D: Extended lifespan ■ (medium)

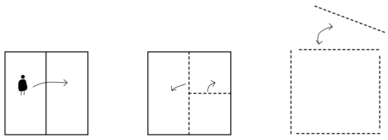
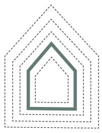
Non load-bearing inner walls ***or*** ***or demountable inner walls***	Extended lifespan: Itard & Klunder (2007), Rasmussen et al. (2020) Less impact from use and end of life phase: Itard & Klunder (2007), Rasmussen et al. (2020)		B5: Itard & Klunder (2007), Rasmussen et al. (2020) D: Extended lifespan
Design for disassembly ***or*** ***Separate/ separable construction layers***	Extended lifespan: Graham (2005), Eberhardt et al. (2019), Minunno et al. (2020) Less impact from use and end of life phase: Rasmussen et al. (2020), Minunno et al. (2020)	A1-A5: Doesn't necessarily mean an increase (Slaughter, 2001; Rasmussen et al., 2020)	B2/B4: Slaughter (2001) B5: Rasmussen et al. (2020), Minunno et al. (2020) C1-C4: Minunno et al. (2020) D: Eberhardt et al. (2019), Minunno et al. (2020)
Accessible/ interchangeable subsystems and components (services)	Extended lifespan: Graham (2005), Schneider & Till (2007) Improved life cycle performance: Russell & Moffatt (2001)	A1-A5: Doesn't necessarily mean an increase (Slaughter, 2001; Rasmussen et al., 2020)	B2/B4: Slaughter (2001) B6: Increased operational performance D: Extended lifespan

5.3 Explanation of figures

Table 10 explains the figures used in the presentation of the results of the qualitative assessment in Table 11. An LCA performed by Liljenström et al. (2015) is used as reference, where the distribution of climate impact from the life cycles modules have been roughly translated into different size of circles. Because the impact from the use phase depends on the reference study period and scenarios the sizes of these modules are chosen more arbitrarily. Furthermore, B5 is not included in the study by Liljenström et al. (2015), so its size is set to the same as B2 and B4.

Table 10 Explanation of figures found in Table 11.

	Size of impact from life cycle modules A1-A5, B2, B4, B5, B6 and C1-C4 of a reference case. Relation estimated from Liljenström et al. (2015)
	Design strategy assessed to give an increased climate impact to the life cycle module
	Design strategy assessed to give a decreased climate impact to the life cycle module
	Design strategy enabling an extended lifespan/ multiple life cycles to the building
	Design strategy enabling an extended lifespan/ multiple life cycles to building components

	Indication of which category of design for flexibility the design strategy implies; flexibility in social use, flexibility in physical use or flexibility in material/technical use, see Section 4.1.2
	Indication of which building layer the design strategy influences, see Section 2.4.2 and Figure 3

5.4 Result of qualitative assessment

Table 11 presents the result from the qualitative assessment. The assessment provides insights into the potential of each design strategy to reduce the climate impact over the life cycle. Further, it serves as a basis for the subsequent case study.

From the qualitative assessment one can draw the conclusion that some design strategies mean a potential decrease of climate impact in a long-term time perspective (the cradle to grave impact) with or in some cases without an increase of climate impact in the building phase (the cradle to gate impact). The balance between the increase and decrease is unidentified however. Also, the benefits that can be gained in a long-term perspective are scenario based, thus are not certain. The benefits that this applies to could be all of the defined environmental benefits; *extended lifespan*, *decreased climate impact from maintenance, repair, replacement, refurbishment and end of life, improved lifecycle performance* and *more efficient use of space.*

One can also draw the conclusion that some design strategies mean a potential decrease of climate impact in the building phase, which can be seen as a benefit on a short-term perspective. These are the strategies that enable *more efficient use of space*. However, as for instance Russel and Moffatt (2001), Schneider and Till (2007) and Slaughter (2001) point out, many design strategies mean a more *efficient use of space* over time as well, as spaces will on average be used more.

Table 11 Qualitative assessment of chosen design strategies.

Design strategy	Life cycle module (see Figure 2) in which potential climate impact reduction and possible increase is realized: **A1-A3**, **A4-A5**, **B2, B4**, **B5**, **B6**, **C1-C4**, **D** Benefits of extended life or multiple life cycles	Time span of potential climate benefits: **Short**	**Long**	Design parameter (see Table 3)	Category of flexibility (see Table 3 and Figure 5)	Main building layers where change is enabled (see Figure 3)
Functionally neutral rooms /Loose fit rather than slim fit			X	Geometry/ floor plan		
Sliding/ movable walls and Foldable furniture		X	X	Geometry/ floor plan		
Non load-bearing/ demountable inner walls			X	Geometry/ floor plan		
Placement of service core *Geometrical regularity of plan*			X	Geometry/ floor plan		
Increased floor height			X	Geometry/ floor plan		
Structural redundancy			X	Material/ services		
Design for disassembly / separate layers			X	Material/ services		
Accessible/ interchangeable sub-systems and components (services)			X	Material/ services		

6 Case study- LCA of design strategies for flexibility

In the following chapter, chosen design strategies to achieve design for flexibility are quantitatively assessed through an LCA, applied on a multi-family residential building called Varvsporten. The LCA compares two cases, one reference case and one flexible case. Furthermore, it considers a first and a second building life cycle.

6.1 Introduction- Categories and design strategies

According to the literature review and qualitative assessment, *flexibility in material/technical use*, category 3 defined by this thesis, is assessed quantitatively to a larger extent in previous LCA studies. *Flexibility in social and physical use,* Category 1 and 2, on the other hand is assessed quantitatively to a lesser extent, see Figure 5, Table 5 and Table 10. Furthermore, *flexibility in social and physical use* can arguably be considered as part of early design decisions, since it addresses *geometry and plan*, see Table 3. Therefore, *flexibility in social use and physical use* is chosen to be of focus in the case study.

Design strategies are applied to the flexible case, whilst the reference case is represented by the original design. A wide range of design strategies are defined by this thesis, see Table 3, but only a few are chosen. In order to compare and contrast parameters, strategies resulting in benefits and impacts over the whole life cycle are chosen. Further, strategies are chosen that imply an increased climate impact in the building phase as a way to compare drawbacks and benefits. Therefore, the design strategies *functionally neutral rooms* and *increased floor height* are applied in the case study. The design strategies are further explained in Section 4.1.4 and 6.4.1.

6.2 LCA framework- Goal and scope

The goal of the case study is to examine the climate benefits of design for flexibility from a life cycle perspective. It examines what benefits can be gained from an ease of future change and avoidance of premature obsolescence and thus a potentially *extended lifespan*. Further, it examines what benefits can be gained from using a defined space in different ways and thus enabling a *more efficient use of space*. Further, the case study applies methodological choices that were found in the literature review, see Figure 6. The results are meant to contribute to a dialogue on the climate benefits of flexibility in residential buildings, but also contribute to a discussion on how design strategies such as flexibility can be accounted for in LCAs for the inherent values to be appreciated. The specific question to be answered is:

- What are the possible climate benefits from *extended lifespan* and more *efficient use of space* enabled by design for flexibility?

6.2.1 Scope of the study

The LCA that is conducted is of the type attributional. The study is performed with BM (Byggsektorns miljöberkningsverktyg) version 1.0 with IVL’ s climate database, OpenLCA version 1.10.3 with the data base Ecoinvent version 3.2 as well as spreadsheets.

6.2.1.1 Functional unit

The literature review revealed that the functional unit is important when considering space efficiency and occupancy (Francart et al., 2020; Bastos et al., 2014). Therefore, the functional unit *m^2 BOA and year*, will be used in combination with *apartment and year* in order to fairly evaluate the climate impact of changing floor plans. Further, the functional unit *person, apartment and year* will be used to account for occupancy. The apartment used in the functional unit is described further in Section 6.3.1.

6.2.1.2 Impact category

The focus of this thesis is on the environmental impact climate change. Therefore, the choice of impact categories is limited to climate change with the categorization factor GWP_{100} (global warming potential in a time perspective of 100 years) given in kg CO_2 equivalents.

6.2.1.3 System boundaries

Building parts considered are, in accordance to the recommendations of the coming climate declarations, the load bearing structure, room forming elements, facade, outer roof and foundation, see Table 14 for an exhaustive list. Life cycle modules considered are A1-A5 of the building phase, B2 and B4-B5 of the use phase and C1-C4 of the end of life phase, see Figure 7. Differing from the qualitative assessment, the case study excludes energy use, module B6. This is justified because the focus of the case study is on material related impacts, and the category *flexibility in material/technical* use is excluded.

Multiple life cycles are shown to enable accounting for design for flexibility in an LCA, see Figure 6. Therefore, the case study considers one and two building life cycles. When considering two life cycles, the second one starts when the building is either refurbished or demolished and rebuilt. This means that refurbishment, (B5) is only included when considering two life cycles. Two allocation methods are used to determine what each life cycle is responsible for. The first allocates the impacts directly caused by each life cycle to the respective cycle, according to the cut off approach (Baumann & Tillman, 2004). The second, similar to Eberhardt et al. (2019) and Tingley & Davison (2012) allocates the impact of all processes, except for of the use phase, equally between the two cycles.

Because of the significance of the reference study period (Marsh, 2017; Eberhardt et al., 2019) and also the high uncertainty of the lifespan of a building, the reference study period of one life cycle is set to 30, 50 and 80 years.

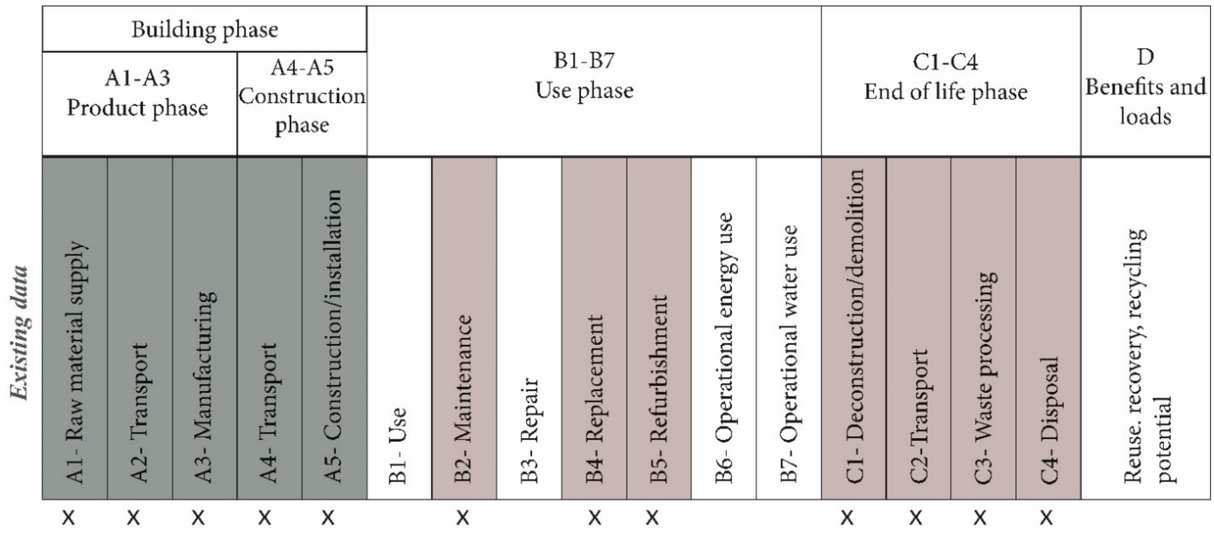


Figure 7 Life cycle modules included in the case study are noted with an x. The original calculations of A are performed by IVL and the calculation for B and C are calculated in this study.

6.2.1.4 Data collection

Building phase (A1-A5)

The calculations of the building phase are based on a pre-existing calculation report for a pilot study of multi-family housing within a project financed by Vinnova and within LFM30. It is conducted in BM and the data represent Swedish generic data from IVL' s climate database and, to a smaller degree, specific data from EPDs and transport scenarios. See Appendix II for the calculation report.

Use phase (module B2, B4 and B5)

The building elements included in maintenance and replacement are based on reports by Liljenström et al. (2015) and Larsson et al. (2016) and the respective intervals are based on a report by IVL summarizing lifespans, maintenance and recycling scenarios of building components (Erlandsson & Holm, 2015). The LCA data for production of new materials is based on the climate data for modules A1-A5, or if needed from the data base Ecoinvent 3.2, and the LCA data for the end of life treatment of the replaced materials is based on the climate data for modules C1-C4.

End of life phase (module C1-C4)

The end of life scenarios of the building elements are based on reports by Erlandsson and Holm (2015), Liljenström et al. (2015) and Larsson et al. (2016). The LCA data is from the data base Ecoinvent 3.2 modelled in OpenLCA. The chosen data from Ecoinvent represent European generic technology, as Swedish specific data is not available.

6.2.1.5 Delimitations and general assumptions

Some delimitations and assumptions are made due to lack of time and data. The following points describe general delimitations and assumptions, whilst specific calculation assumptions are described further in Section 6.5.

- Some building parts are excluded, mainly the inner surfaces, installations and ground.

- Some assumptions regarding the building composition are made based on floor plan drawings and the resource compilation of the pre-existing LCA performed in BM.
- The balcony and balcony access are included in the category “floor” in the BM model, therefore their share of the weight is estimated based on floor plan drawings.
- Dynamic LCA is not considered. For instance, this means that no consideration is taken to future energy efficiency and technological development of the use and end of life phase.
- The study is limited to one apartment type of Varvsporten. Some assumptions to do this limitation are made, which are further described in Section 6.3.1.
- When changes to the design of the apartment are made, some assumptions on how it affects the quantity of each building element are made. It is assumed that when the material quantity of one building component changes, the elements included in that component change with the same percentage.

6.3 Object of study: Brf Varvsporten

Varvsporten is a multi-family residential building that at the time of this thesis is under development by PEAB Bostad AB, and is part of a larger development area in Malmö, Sweden called Varvsstaden (PEAB, n.d). The building consists of different apartment types, ranging from one to six RoK (rooms and kitchen) of 23-156 m^2 BOA. Most apartments are further considered space efficient. See Appendix V for floor and site plans. Table 12 describes some general characteristics of the building.

Table 12 Description of Varvsporten (PEAB, n.d.; M. Svensson, personal communication, November 5, 2020).

Number of apartments	**Number of different apartment types**	**Number of floors**	**BOA**	**BTA**
116	22	7-11	6546 m^2	8786 m^2

6.3.1 Part of building under study

Because the reference case is represented by the original design and the flexible case includes design alterations (see Section 6.4.1), the study is limited to one apartment type of Varvsporten. The chosen apartment type is summarized in Table 13 and the floor plan is shown in Figure 9 and Appendix V.

Because of the limitation to one apartment type a share of the building’s total climate impact is allocated to the apartment. This is done by allocating the same share of the total climate impact to the apartment as its share of the total BOA according to equation (1). This relationship is also applied when allocating the share of the total mass of each building element to the apartment. When presenting results, “apartment” is used instead of “building”. This is because, uncertainties are introduced if assuming that the change in material use (due to the design alterations) can be applied to the whole building, when this would actually need thorough floor plan studies as the building consists of a variety of apartment types.

$$\frac{BOA_{apartment}}{BOA_{whole\ building}} = \frac{kg\ CO_2{-}eq_{apartment}}{kg\ CO_2{-}eq_{whole\ building}} \tag{1}$$

Table 13 Description of the apartment type chosen for study (PEAB, n.d.).

Type of apartment	BOA	Room height	Number of the apartment type	Share of tot BOA
2 RoK	51 m^2	2.5 m	34	0.78%

6.3.2 Building components

Table 14 shows the building parts, building components and respective elements included in the study. As the data is taken from the resource compilation of BM, the building parts are presented according to the same structure, which is the SBEF (BSAB 83) codes (IVL, 2020), a classification system for the Swedish building sector.

Table 14 Included building parts, components and elements based on pre-existing calculations in BM and delimitations by this study.

Building part	Building component	Building element
Load bearing structure		
	Walls	Reinforced concrete
		Prefabricated concrete walls
		Glass wool insulation
		Shuttering plywood
	Floors (including balconies and balcony access)	Reinforced concrete
		Prefabricated concrete slabs
		Shuttering plywood
		Glass wool insulation
		Gypsum boards
		Steel studs
		Clay aggregated blocks
	Staircases	Reinforced concrete
	Studs	Steel
Room forming elements		
	Non load bearing inner walls	Plywood
		Gypsum boards
		Glass wool insulation
		Steel latches
Facade		
	Curtain walls	Plywood
		Sealing strip
		Gypsum boards
		Cellulose insulation
		Glass wool insulation
		Acoustic board
		Steel studs
	Outer surface	Bricks
		Shale
	Windows and doors	Windows with wood/aluminium frame
		Glass wool insulation
		Gypsum board
		Wood head /casing
		Front doors
Outer roof		
	Roof construction	Reinforced concrete
		Gypsum boards
		Glass wool insulation
		Prefabricated concrete slabs

		Wood boards (tounged and grooved) and joist
		Plywood
		Wood surface boards
	Outer surface	Aluzinc steel sheet
	Roof eaves	Wood surface boards
		Plywood
		Wood studs
		Cellulose insulation
	Roof trusses	Cross laminated timber
	Terrasses	EPS insulation
		Reinforced concrete
		Wood studs
Foundation		
		Gypsum boards
		Glass wool insulation
		Prefabricated concrete slabs
		Shuttering plywood
		Reinforced concrete
		Clay aggregated blocks
		Shuttering plywood
		EPS insulation

6.4 Design for flexibility assumptions

In this section the design alterations made to the flexible case as well as scenarios of the two cases are described.

6.4.1 Design strategies of the flexible case

In order to account for the design specifications of flexibility, design alterations are made to the chosen apartment of study. As previously described the design strategies *functionally neutral rooms* and *increased floor height* are chosen, for more description see Section 4.1.4.1.

Good general room dimensions are according to Eringstam and Sandahl (2018) 3.6 x 3.6. The width of the bedroom and living room is therefore increased to these dimensions. Further, according to Eringstam and Sandahl (2018) the room height for public rooms should be 2.7 m or more. Therefore, to allow for a future change of function from housing to public, the floor height is increased from 2.5 m to 2.7 m. Figure 8 shows the concept of the design strategies and Figure 9 shows the apartment according to its original design (the reference case) and with the above-described design alterations (the flexible case). Table 15 shows the floor area and height of respective cases.

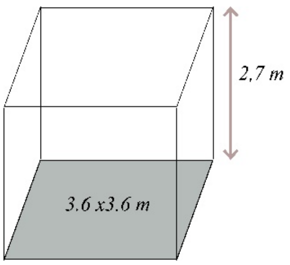


Figure 8 Concept of the design alterations made to the apartment; functionally neutral room sizes and increased floor height.

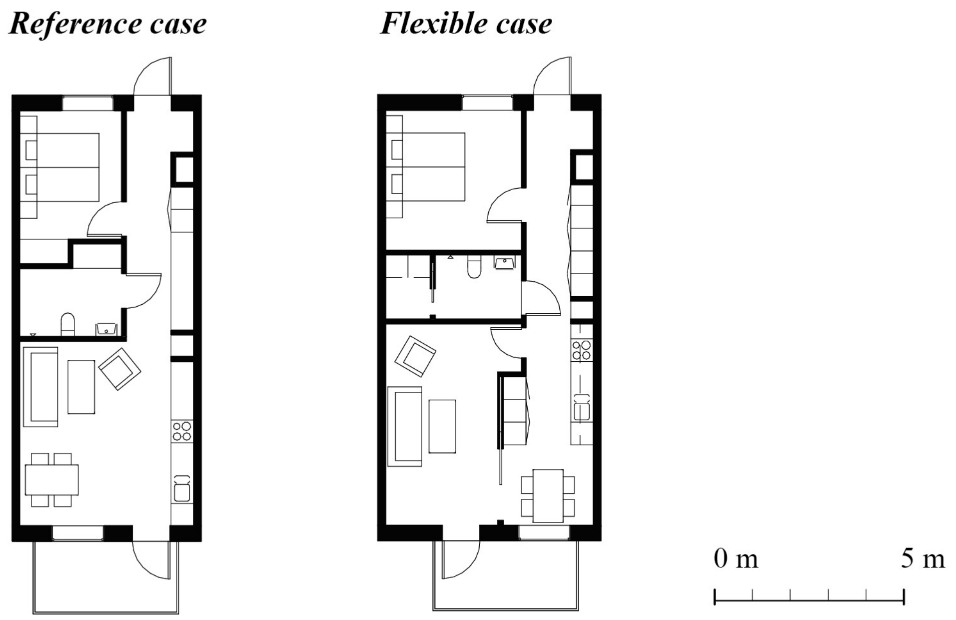


Figure 9 *To the left- the apartment in its original design (reference case). To the right- the apartment with its altered design (flexible case). The scale is 1:200.*

Table 15 *BOA and floor height of the apartment of the reference and flexible case.*

Reference case		**Flexible case**	
BOA	**Floor height**	**BOA**	**Floor height**
51 m^2	2.5 m	58.5 m^2	2.7 m

6.4.1.1 Discussion on achieved flexibility

Discussions made 20 November 2020, with Anna Braide, an architect and researcher at Chalmers University of Technology with a PhD on flexible housing, gave knowledge on the attained qualities of the flexible case. Interpretations made by the author were thereafter made that are described here.

The design alterations give an assumably more flexible floor plan, through increased useability and multifunctionality. Increased useability is hypothetically achieved because the plan allows for different user constellations. The reference case will most likely be occupied by one person or by a couple. The flexible case can, expect for this, also allow for two people who don’t know one another well or even three people to live together and still maintain a balance between private and public spaces. The living room area can act as a living room or a bedroom, which means that there can be two bedrooms or that the bedroom and living room can shift place with one another. The latter is a quality because it gives the choice to not have the bedroom next to the balcony access holding the entrance. Thus, within the predefined space of the apartment the choice is given to adjust according to needs. The dimensions of the floor plan and the room height also allows for other functions to take place, with and without the need for refurbishment. Without making any refurbishments, this could be like above described by changing a bedroom into a living room, but could also be changing it into an at home working space or a smaller office space. The ability to make functional changes through refurbishment requires more detailed investigations of the floor plan to make certain claims, but hypotheses can still be made. For instance, it can hypothetically be assumed that two apartments can be joined together to make bigger apartments or to make office spaces.

Altogether, this means that supposedly, *flexibility in social and physical use* is enabled, as the space can be used in several ways both without and with physical alterations. According to the literature review and qualitative assessment, this in turn means that the building can supposedly be used more efficiently and the risk of it to become obsolete is minimized.

6.4.1.2 Change of material use in the building phase due to design alterations

Table 16 shows the change of material use in the building phase of the flexible case compared to the reference case. It is calculated based on the change of respective component area measured in a 3D model. The walls, floor, inner walls, curtain walls, outer surface and windows are measured directly in the model, whilst the roof and foundation are estimated based on the number of floors of the building. An estimation of the roof and foundation is done in the following way; because the building has 7 to 11 floors, an estimation is made by dividing the change in material of the floor by the average number of floors (which is 9).

Table 16 Calculated and estimated change of material use in the building phase by building component of the flexible case compared to the reference case, due to design alterations.

Building component	**Change of material use due to design alterations**
Load bearing structure	
Floors (excluding balcony and balcony access)	+15%
Walls	+1%
Stair cases	+0%
Room forming elements	
Inner walls	+26%
Facade	
Curtain wall	+42%
Outer surface	+42%
Windows and doors	+0%
Roof	
Roof construction	+2%
Outer surface	+2%
Terrasse	+0%
Foundation	+2%

6.4.2 Scenarios of the use phase

Scenarios of the use phase are modelled for the reference and the flexible case respectively. This includes scenarios of refurbishment and longevity which is modelled by accounting for two life cycles as well as occupancy.

6.4.2.1 Refurbishment and longevity

If considering long lifespans, it can be assumed that the desired function and use of a building will change and so if a building has the ability of accommodating change, and is maintained decently, its lifespan has large potential to be prolonged (Gervasio & Dimova, 2018). With a longer lifespan it is therefore assumed, in this case study, that an upgrade and/or change of function or use of the building is needed and consequently, the flexible case is assumed to have a longer lifespan compared to the reference case. This is modelled by accounting for two life cycles. Scenarios are modelled according to Figure 10, so that, at the end of the first life cycle, which is set to 30, 50 or 80 years, it is assumed that the desired use and function of the building has changed and will either be refurbished (flexible case) or demolished and rebuilt (reference case). Since the largeness of a refurbishment can vary a lot, three scenarios of its extent are included, to account for this sensitivity. The reference case is assumed to be demolished without any refurbishment changing or upgrading its function during its life cycle for comparison. The four scenarios are the following:

- ***Reference case scenario (R)-*** *Demolished and rebuilt once obsolete*
- ***Flexible case scenario one (F1)****- Minimal changes to the floor plan are required, rearrangement of the non-load bearing inner walls is included*
- ***Flexible case scenario two (F2)-*** *Rearrangement of the non-load bearing inner walls and 25 % of the loadbearing walls*
- ***Flexible case scenario three (F3)-*** *Only the load bearing concrete structure is kept.*

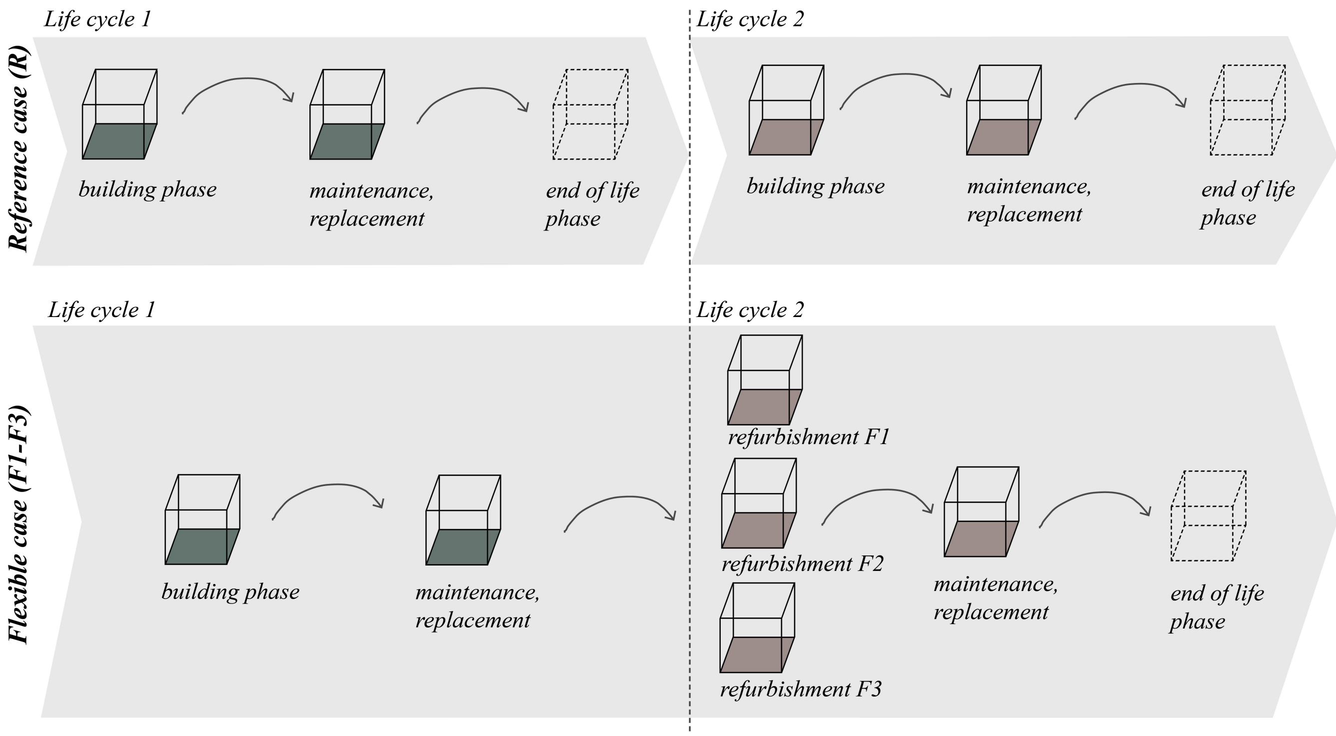


Figure 10 Illustration of modelled scenarios of the reference and flexible case for one and two life cycles. The different colours of the "boxes" indicate different use and/or function of the buildings. The reference study period of two life cycles is either 30+30 years, 50+50 years or 80+ 80 years.

6.4.2.2 Space efficiency

Through the ability to adapt to different family sizes, constellations or functions, a flexible building has the potential to be used more efficiently on average during the life time (Russell & Moffatt, 2001; Magdziak, 2019). For the flexible case it is therefore assumed that there is potential for more efficient use of space.

Space efficiency can, according to the literature review, occur through design strategies that increase the use of a building on average throughout its lifespan or from "start". The latter refers to contracting the space by allowing for quick changes, for example through the design strategies *sliding/ movable walls*, see Table 11. In this case study the idea of space efficiency is explored through design strategies that expand the space rather than contract and thereby has the potential to be used more on average over the building lifespan.

According to Francart et al. (2020) and Bastos et al. (2014), space efficiency can be measured by using a functional unit that is occupancy based. In the case study, an occupancy based functional unit is therefore be applied to the results. In order to estimate the average occupancy of the reference and flexible case, figures from Sveby (2012) and SCB (2019), see Table 17, are used together with hypothetical user scenarios described in Section 6.4.1.1. It is assumed that the reference case is continuously used as a 2 RoK apartment meaning an average occupancy of 1.57. The flexible case is assumed to be used as a 2 and a 3 RoK apartment. If taking an average value of respective occupancy in Table 17, an average occupancy of the flexible case becomes 1.88.

Table 17 Recommended occupancy of different apartment types according to Sveby (2012) and SCB (2019) and an average used for the case study.

Number of rooms	Average occupancy (Sveby, 2012)	Average occupancy (SCB, 2019)	Average occupancy
1 Room and kitchen	1.42	1.3	1.36
2 Rooms and kitchen	1.63	1.5	1.57
3 Rooms and kitchen	2.18	2.2	2.19
4 Rooms and kitchen	2.79	2.9	2.85

6.5 Inventory- Data collection and calculation assumptions

In this section the inventory is explained for the different life cycle phases, including data collection and calculation assumptions. For more detailed inventory data, see Appendix I.

6.5.1 Building phase (module A1-A5)

The calculation of the climate impact from module A1-A5 is based on a pre-existing calculation report made for a pilot study of multi-family housing within a project financed by Vinnova and within LFM30. The pre-existing calculation is made in BM and with IVL's climate database and the result is shown in Figure 11. Module A1-A3 and the load bearing structure stands for the largest share of the climate impact. See Appendix II for full calculation report.

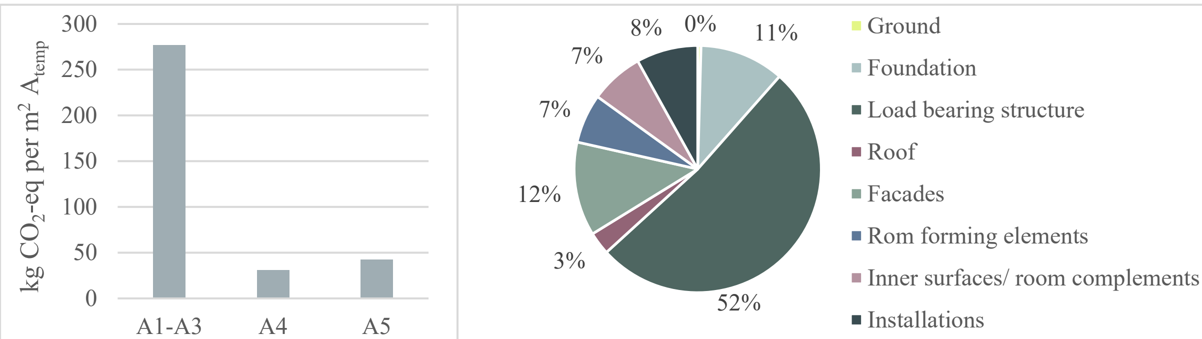


Figure 11 Climate impact from the modules A1-A5 in kg CO_2-eq per m^2 A_{temp} and the contribution from building parts as given by the pre-existing calculations made in BM. Includes the product stage A1-A3, transportation A4, waste management of residues and construction and installation processes of A5.

For the case study, some alterations are made to the prior calculations, based on descriptions made in previous sections. It includes a limitation to one apartment type, see Table 13, a delimitation of building elements, see Table 14 and another design version, see Section 6.4.1.

6.5.2 Maintenance and replacement (module B2 and B4)

A distinction between replacement (B4) and refurbishment (B5) is made for the purpose of this study. All replacement to withhold the function and performance of the building is calculated as replacement in module B4, while replacements to alter or upgrade the function or use of the building is calculated as refurbishment in module B5. Because of uncertainties regarding actual maintenance and replacement intervals, they are further modelled independent of the refurbishment intervals. This means that when considering two life cycles, maintenance and replacement is accounted for during the whole of the reference study period of two life cycles for the flexible case, whilst for the reference case the interval count “starts over” when a new life cycle begins. The calculations of the climate impact of modules B2 and B4 are made according to equation (2), where I stands for climate impact.

$$I_{B2,B4} = I_{A1-A5}\ new\ building\ elements + I_{C1-C4}\ replaced\ building\ elements \tag{2}$$

The calculations of B2 and B4 only include outer measures. For instance, because inner surfaces are excluded from the study they are not considered. All replacements are assumed to be made by the same components and elements with the same quantity as the original one.

The intervals of B2 and B4 are based on a report by Erlandsson and Holm (2015) and it is assumed that the building is in a normal protected setting, as oppose to protected or exposed. Table 18 and 19 shows which building elements and measures that are included as well as the intervals and corresponding number of times for the intervention during a reference study period of 30, 50 and 80 years and counting for one and two life cycles. If the service life of a building element is longer than the reference study period no replacement is considered. According to EN 15978 only whole number of replacements are counted and is to be rounded upwards (SIS, 2011). If the relationship between the service life and the reference study period is such that only a few years remain of the reference study period, then the likelihood of that replacement should ideally be considered (SIS, 2011). However, this is not regarded in the case study, so for instance shale cladding, that has a service life of 75 years will be replaced once with a reference study period of 80 years.

Data is retrieved from modules A1-A5 and C1-C4 as described by equation (2). However, data for paint is missing for modules A1-A5, and is therefore added from Ecoinvent. For specific data sets and assumptions, see Appendix I. Calculations of the amount of material that is subject to maintenance is described in Appendix III.

Table 18 Interval of maintenance (B2) of building elements and the respective number of interventions for 30, 50 and 80 years and one respective two life cycles included in the study. Based on studies by Erlandsson and Holm (2015), Liljenström et al. (2015), Larsson et al. (2016) and Kahangi et al. (2020).

Building element	**Maintenance intervention**	**Interval of maintenance (years)**	**30 years**	**50 years**	**60 years**	**80 years**	**100 years**	**160 years**
Bricks	New external mortar, 25 mm	25	1	1	2	3	3	6
Windows	repainting	10	2	4	5	7	9	15
Doors	repainting	10	2	4	5	7	9	15
Aluzinc steel sheet	repainting	12	2	4	4	6	8	13
Balcony concrete slab	5% replaced	25	1	1	2	3	3	6
Balcony access concrete slab	5% replaced	23	1	2	2	3	4	6

Table 19 Intervals of replacement (B4) of building elements and the respective number of replacements for 30, 50 and 80 years and one respective two life cycles included in the study. Based on studies by Erlandsson and Holm (2015), Liljenström et al. (2015) and Larsson et al. (2016).

Building element	**Interval of replacement (years)**	**30 years**	**50 years**	**60 years**	**80 years**	**100 years**	**160 years**
Bricks	80	0	0	0	0	1	1
Shale	75	0	0	0	1	1	2
Windows with wood/aluminium frame	40	0	1	1	1	2	3
Doors	40	0	1	1	1	2	3
Aluzinc steel sheet	40	0	1	1	1	2	3
Balcony concrete slab	60	0	0	0	1	1	2
Balcony access concrete slab	70	0	0	0	1	1	2

6.5.3 Refurbishment (module B5)

Refurbishment is only included when considering two life cycles and only for the flexible case, see Section 6.4.2.1. According to the scenarios described in Section 6.4.2.1, different extents of refurbishment are calculated. Table 20 shows which building components that are included in the refurbishment scenarios. If nothing else is indicated it is assumed that 100 % of the building components included in the refurbishment are replaced. It is only in the flexible case scenario 2 and 3 that 25 % of the walls are considered for replacement. It is further assumed that they are replaced with the same building component and of the same quantity. Replacements as a result of refurbishment (B5) does not include replacements of the replacement phase (B4) presented in Table 19. The calculation of the climate impact of module B5 is made according to equation (3), where *I* stands for the climate impact.

$$I_{B5} = I_{A1-A5}\, new\ building\ components + I_{C1-C4}\, replaced\ building\ components \quad (3)$$

Table 20 Refurbishment of the flexible case scenario 1, 2 and 3 as well as demolition and rebuilding of the reference case scenario. "Yes" means that the component is replaced and "no" that it is kept. Replacements in module B4 are not included.

Building component	**Flexible case scenario 1 (F1)**	**Flexible case scenario 2 (F2)**	**Flexible case scenario 3 (F3)**	**Reference case scenario (R)**
Load bearing structure				
Floors	no	no	no	yes
Walls	no	yes (25%)	yes (25%)	yes
Stair cases	no	no	no	yes
Room forming elements				yes
Inner walls	yes	yes	yes	yes
Facade				
Curtain wall	no	no	yes	yes
Outer surface	no	no	yes	yes
Windows and doors	no	no	yes	yes
Roof				
Roof construction	no	no	yes	yes
Outer surface	no	no	yes	yes
Terrasse	no	no	no	yes
Foundation	no	no	no	yes

6.5.4 End of life phase (module C1-C4)

The reference case reaches its end of life after one life cycle and the flexible case after two life cycles. The LCA data is from Ecoinvent 3.2 and is modelled in OpenLCA. In Figure 12, a flowchart of the end of life system is shown, the system boundary illustrates which processes are included in the OpenLCA modelling. For materials going to deposit or incineration, pre-processing is excluded as it is assumed to be small, an exception however is wood, where the process of crushing and shredding is included. For materials that are recycled, processing is included, marked with C3 in Figure 12. The end of life scenario of each building material is described in Table 21, on which the calculations are based on.

According to the standard EN 15978 the end of life should be modelled based on the "polluter pays principle" (SIS, 2011). This means that the impact from getting rid of the material and making it in a state so that it is recyclable is allocated to the building. If the process delivers energy such as heat recovery from an incineration process it would be included in module D. Likewise the benefits from recycling would be allocated to module D. However, since module D is excluded from the study, no benefits from heat recovery and recycling are included in the calculations, see Figure 12.

Energy for deconstruction, in module C1, only burdens structural materials according to the datasets of Ecoinvent (Doka, 2009). According to the datasets used from Ecoinvent this means that concrete, reinforcement, brick, shale and gypsum boards are burdened with energy for deconstruction, whereas the remaining materials are only burdened with dismantling of the component itself. A generic value of 15 km is used for the distance of transportation in module C2 based on Liljenström et al. (2015) and the lorry used for transportation is assumed to be the same for all building elements. If data from Ecoinvent was not found for a specific material, then similar materials were used in its place. If unknown what a typical end of life scenario is for a material, it was assumed that it goes to deposit, however the share of these elements is assumed to be small. For specific data sets and assumptions, see Appendix I and for examples of product systems modelled in OpenLCA, see Appendix IV.

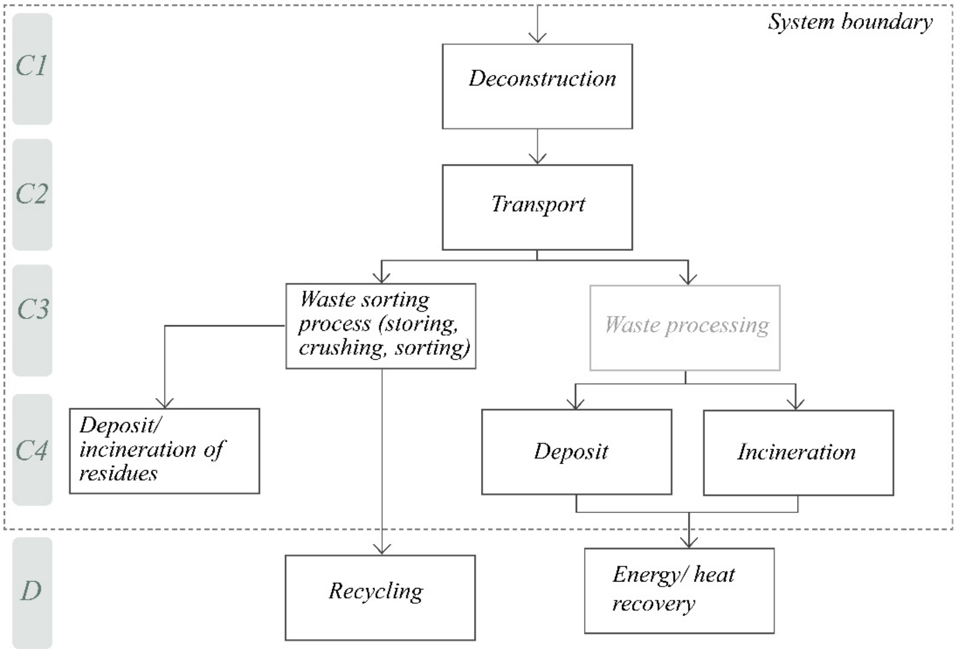


Figure 12 *Flowchart of the end of life phase showing which processes are included in the system boundary. The process "waste processing" is grey because it is excluded from the calculations for deposit and incineration scenarios, except for wood. Next to each process the life cycle module C1-C4 (and D) it corresponds to is stated.*

Table 21 *End of life scenario for building materials. Based on studies by Erlandsson and Holm (2015), Liljenström et al. (2015) and Larsson et al. (2016).*

Building material	**End of life scenario**
Concrete	Crushed and recycled as road filling
Reinforcement	Recycled
Glass wool insulation	Placed at deposit
Gypsum boards	Placed at deposit
Steel	Recycled
Cellulose insulation	Incinerated as energy recovery
EPS insulation	Incinerated as energy recovery
Window frames	Recycled
Window panes	Crushed and placed at deposit
Doors	Crushed and incinerated as energy recovery
Bricks	Crushed and recycled as filling material
Shale	Crushed and recycled as filling material
Aluzinc steel sheet	Recycled
Wood products	Crushed and shredded and then incinerated as energy recovery
CLT wood	Crushed and shredded and then incinerated as energy recovery
Clay aggregated blocks	Crushed and recycled as filling material

6.6 Impact assessment

In this section the impact of the reference and flexible case is assessed for the impact category climate change. It is firstly presented as the total impact for two life cycles and then presented according to the building phase, use phase and end of life. The reference study period is set to 50 years and the results are presented for the following functional units:

- Apartment and year
- m^2 BOA and year
- Person, apartment and year.

6.6.1 Total impact for life cycle 1 and 2 (50+50 years)

The total climate impact for two life cycles with a reference study period of 50 years each is shown in Figure 13. It is made according to the scenarios in Figure 10 described in Section 6.4.2. The impact for modules A1-A5 and C1-C4 is larger for the reference case as it after the first life cycle will be demolished and rebuilt, while the flexible case is refurbished and thus burdened with the impact of B5. The size of B5 is dependent on refurbishment scenario. From Figure 13 it is clear that the flexible case has a lower climate impact than the reference case for all refurbishment scenarios and functional units if considering two life cycles.

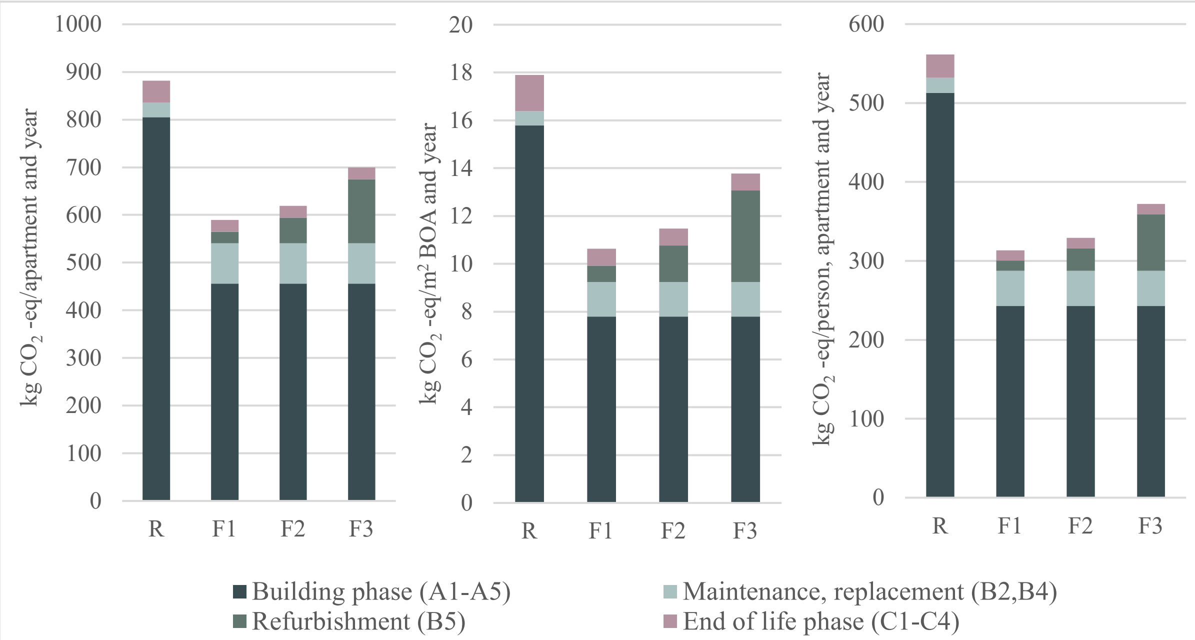


Figure 13 The impact in kg CO_2-eq distributed by life cycle phase over two life cycles with a reference study period of 50 years each. For the functional units apartment and year, m^2 BOA and year and person, apartment and year. R-reference case, F1-flexible case scenario 1, F2-flexible case scenario 2, F3-flexible case scenario 3.

6.6.2 Impact per building phase and 50 years

In this section the impact per building phase will be presented for a reference period of 50 years.

6.6.2.1 Building phase (module A1-A5)

The climate impact from the building phase, module A1-A5 is shown in Table 22 and Figure 14. With the functional unit *apartment and year,* the flexible case has a climate impact that is 13 % larger than the reference case. But with the functional unit *m^2 BOA and year* and *person, apartment and year* the flexible case has a climate impact similar to or less than the reference case. From Figure 14 it is clear that the floor of the load bearing structure has the largest impact but is also sensitive to the choice of functional unit.

Table 22 The impact in kg CO_2-eq from A1-A5 for the reference and flexible case as well as the percentual difference of the flexible compared to the reference case for the functional units apartment and year, m^2 BOA and year and person, apartment and year and the reference study period 50 years. Includes the product stage A1-A3, transportation A4, waste management of residues and construction and installation processes of A5.

Functional unit	**Reference case**	**Flexible case**	**Difference**
kg CO_2-eq/ apartment and year	402.5	456.4	+13 %
kg CO_2 -eq/ m^2 BOA and year	7.9	7.9	+1 %
kg CO_2-eq/ person, apartment and year	256.4	242.7	-4 %

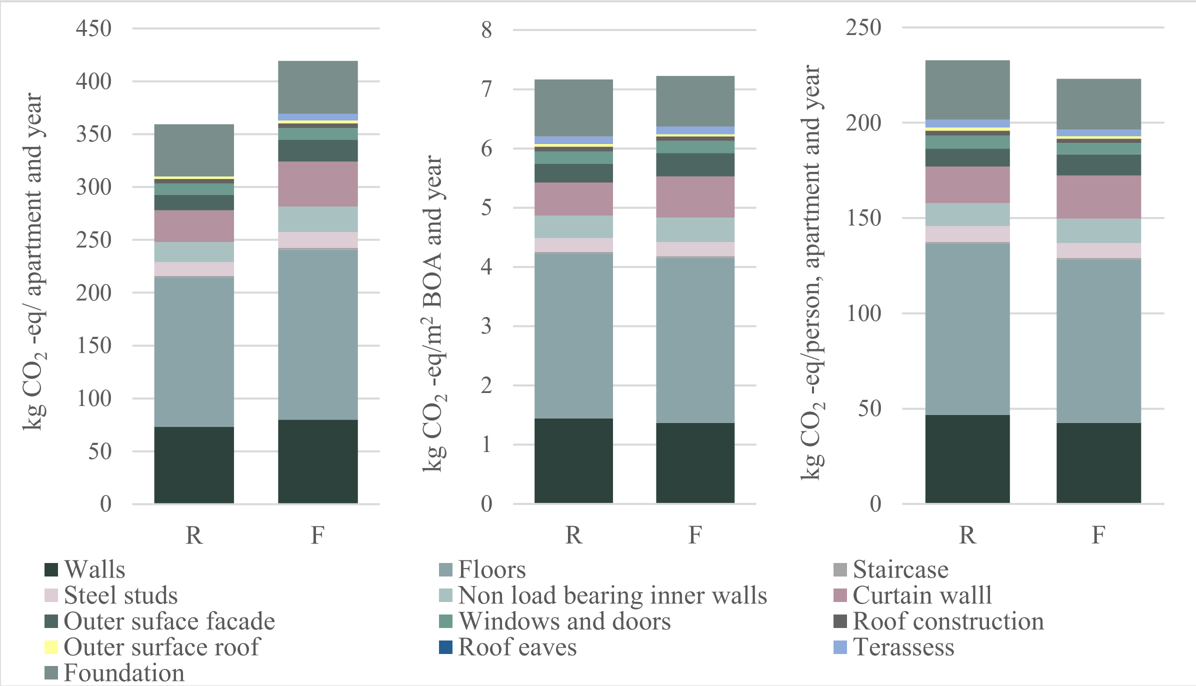


Figure 14 The impact in kg CO_2-eq from A1-A5 distributed by building component for the functional units apartment and year, m^2 BOA and year and person, apartment and year and the reference study period 50 years. Excluding construction and installation processes (A5). R-reference case, F-flexible case.

6.6.2.2 Maintenance and replacement (module B2 and B4)

The climate impact from maintenance and replacement, module B2 and B4, is shown in Table 23 and Figure 15. Both cases are shown for a reference study period of 50 years but the flexible case is also shown for 100 years as when accounting for two life cycles B2 and B4 is accounted for during the total period of two life cycles. The big difference between 50 and 100 years is mainly from replacement of windows, shale and balcony that becomes relevant first after 50 years. With the functional unit *apartment and year,* the flexible case has a climate impact that is marginally larger than the reference case. But with the functional unit *m^2 BOA and year* and *person, apartment and year* the flexible case has a climate impact that is smaller.

Table 23 *The impact in kg CO_2-eq from B2 and B4 for the reference and flexible case as well as the percentual difference of the flexible case compared to the reference case. For the functional units apartment and year, m^2 BOA and year and person, apartment and year and for 50 and 100 years.*

Functional unit	Reference study period (years)	Reference case	Flexible case	Difference
kg CO_2-eq/ apartment and year	50	15.4	15.7	+2 %
	100	-	42.1	
kg CO_2-eq /m^2 BOA and year	50	0.30	0.27	-11 %
	100	-	0.72	
kg CO_2-eq/ person, apartment and year	50	9.8	8.4	-15 %
	100	-	22.4	

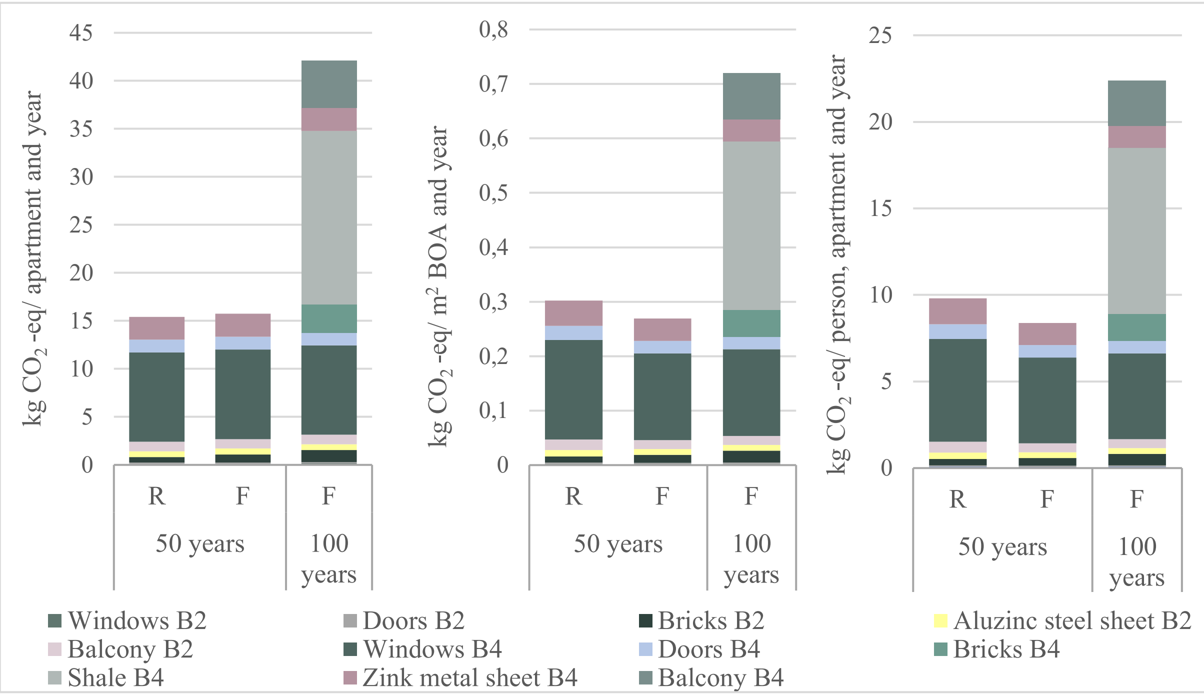


Figure 15 *The impact in kg CO_2-eq from B2 and B4 distributed by building element and module for the functional units apartment and year, m^2 BOA and year and person, apartment and year and for 50 and 100 years. R-reference case, F-flexible case.*

6.6.2.3 Refurbishment (module B5)

The climate impact from refurbishment, module B5, is shown in Table 24 and Figure 16. Even for the refurbishment scenario where only the concrete structure is kept (F3) the impact from refurbishment is considerably less than demolition and rebuilding of the reference case.

Table 24 *The impact in kg CO_2-eq from the refurbishment scenarios of the flexible case and from demolition/ rebuilding of the reference case for the functional units apartment and year, m² BOA and year and person, apartment and year and the reference study period 50 years.*

Functional unit	Reference case R	Flexible case F1	Flexible case F2	Flexible case F3
kg CO_2-eq/ apartment and year	425.5	24.1	53.7	134.7
kg CO_2 -eq/ m^2 BOA and year	8.3	0.4	0.9	2.3
kg CO_2-eq/ person, apartment and year	271.0	12.8	28.5	71.6

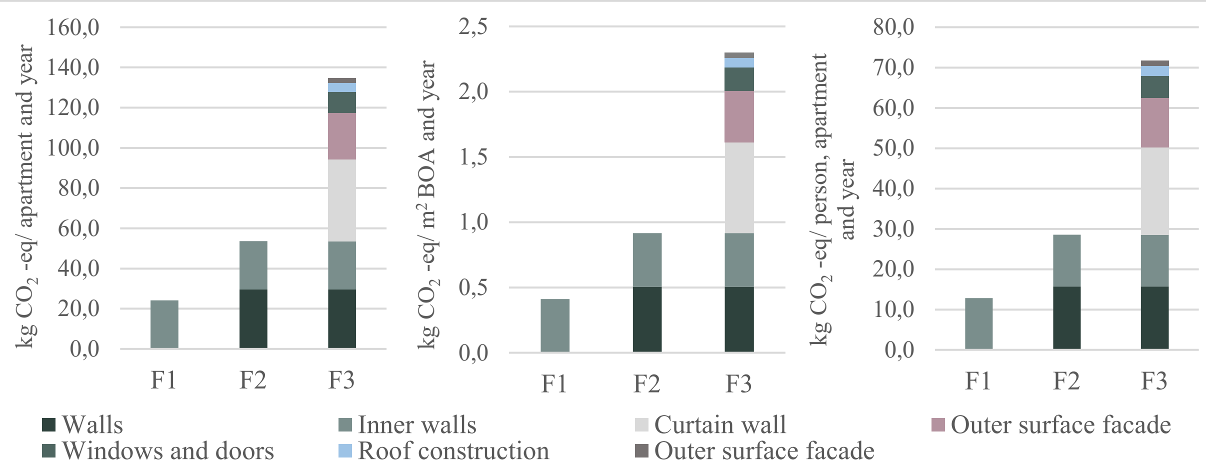


Figure 16 *The impact in kg CO_2-eq from B5 distributed by building component for the functional units apartment and year, m² BOA and year and person, apartment and year and the reference study period 50 years. F1-flexible case scenario 1, F2-flexible case scenario 2, F3-flexible case scenario 3.*

6.6.2.4 End of life phase (module C1-C4)

The climate impact from the end of life phase, module C1-C4, is shown in Table 25. With the functional unit *apartment and year,* the flexible case has a climate impact that is larger than the reference case. But with the functional unit *m² BOA and year* and *person, apartment and year* the flexible case has a climate impact less than the reference case. As depicted by Figure 17, the biggest impact comes from the concrete and EPS insulation.

Table 25 *The impact in kg CO_2-eq from C1-C4 for the reference and flexible case as well as the percentual difference of the flexible case compared to the reference case. Presented for the functional units apartment and year, m² BOA and year and person, apartment and year and the reference study period of 50 years.*

Functional unit	Reference case	Flexible case	Difference
kg CO_2-eq/ apartment and year	23.0	24.8	+8 %
kg CO_2-eq /m^2 BOA and year	0.45	0.42	-6 %
kg CO_2-eq/ person, apartment and year	14.7	13.2	-10 %

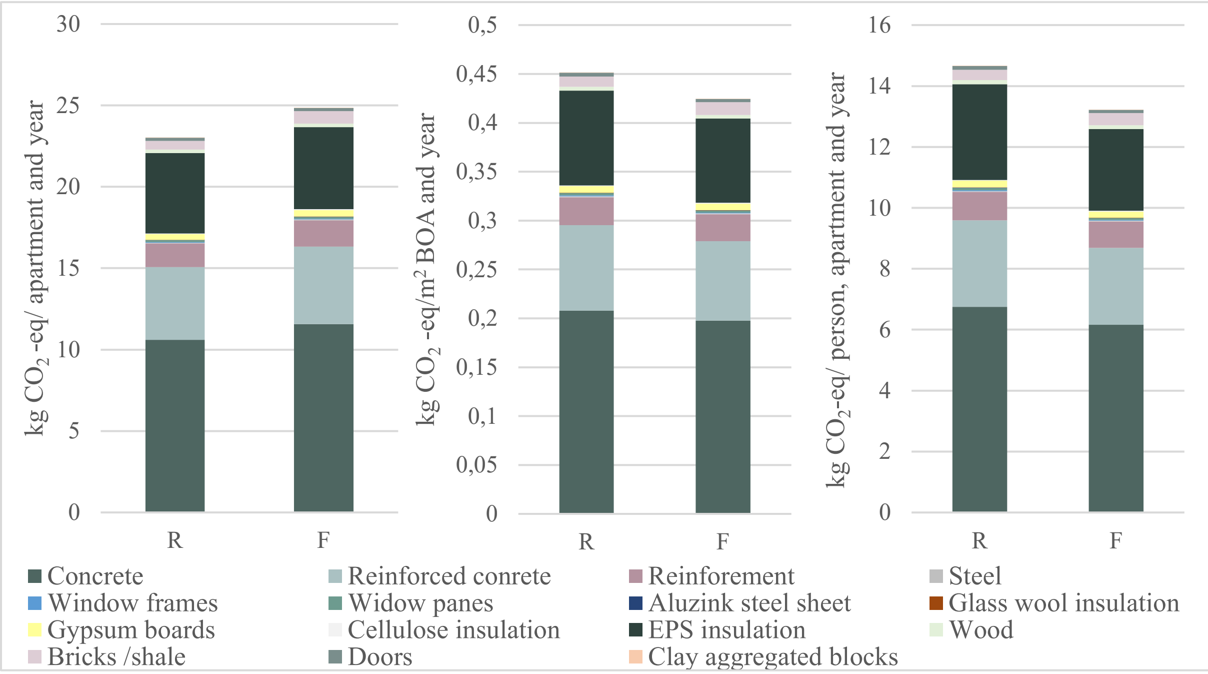


Figure 17 *The impact in kg CO_2-eq from C1-C4 distributed by building element for the functional units apartment and year, m^2 BOA and year and person, apartment and year and the reference study period 50 years. R-reference case, F-flexible case.*

6.7 Interpretation of the case study

In this section the LCA is interpreted and verified. Firstly, a compilation of the impact for one respective two life cycles are made and with a reference study period of 30, 50 and 80 years to test the sensitivity of these methodological choices. Also, when considering two life cycles two different allocation methods are applied to allocate the benefits and impacts between them. Lastly the results are compared to another multifamily residential building and to the literature review and qualitative assessment of this thesis.

6.7.1 The impact when considering one life cycle

Because of the difficulty to predict if the flexible building will stand for two life cycles according to the scenarios of the case study, the impacts are also presented considering only one life cycle, see Figure 18.

When considering a functional unit of *apartment and year*, the flexible case has a climate impact that is higher than the reference case for all reference study periods, see Figure 18. The impact of the flexible case is approximately 14 % higher.

When considering a functional unit of *m^2 BOA and year*, the reference and flexible case have similar climate impacts, see Figure 18. Using a functional unit of *1 m^2* makes the bigger apartment appear better. A possible explanation for this is that the relationship between the wall and floor area might be smaller for a larger building, as was reflected by Bastos et al. (2014). This implies that if the design strategy *increased floor height* would not have been applied to the flexible case, the impact of the flexible case might have been lower than the reference case for a functional unit of *m^2 BOA and year*.

When considering a functional unit of *person, apartment and year*, the flexible case has a lower climate impact than the reference case for all reference study periods, see Figure 18. The impact of the flexible case is approximately 4% lower.

As expected, the longer reference study period the better the climate impact, compared to 30 years, 50 years gives an impact that is 38% lower and 80 years that is 58% lower. The advantage of prolonging the lifespan decreases though the longer it is due to larger impacts from the use phase. In this case study it is due to more maintenance and replacement requirements, see Figure 15. This trend would likely have been more distinct if more elements and life cycle modules were included in the study.

The relationship between the reference study period of the building and the service life of building elements defined in the case study can give a lack of robustness to the results. The calculations of maintenance and replacement are made according to EN 15978, where only whole values are included (SIS, 2011). This means that for instance a period of 50 years is freed from burdens of replacement of elements having a slightly longer service life but is burdened with replacement of elements having a slightly shorter service life.

Even though not further explored in the case study, the relationship between the service life of building elements and of the building has additional effects on the results according to the literature study. If a building element has a service life that is less or equal to the building's then the impact for that element is theoretically not dependent on the building service life compared to an element that has a service life longer than the building's (Marsh, 2017). Hypothetically then, if considering the impact per building part, the concrete structure, with a long service life, has a larger benefit of an increased building life than building elements with a short service life.

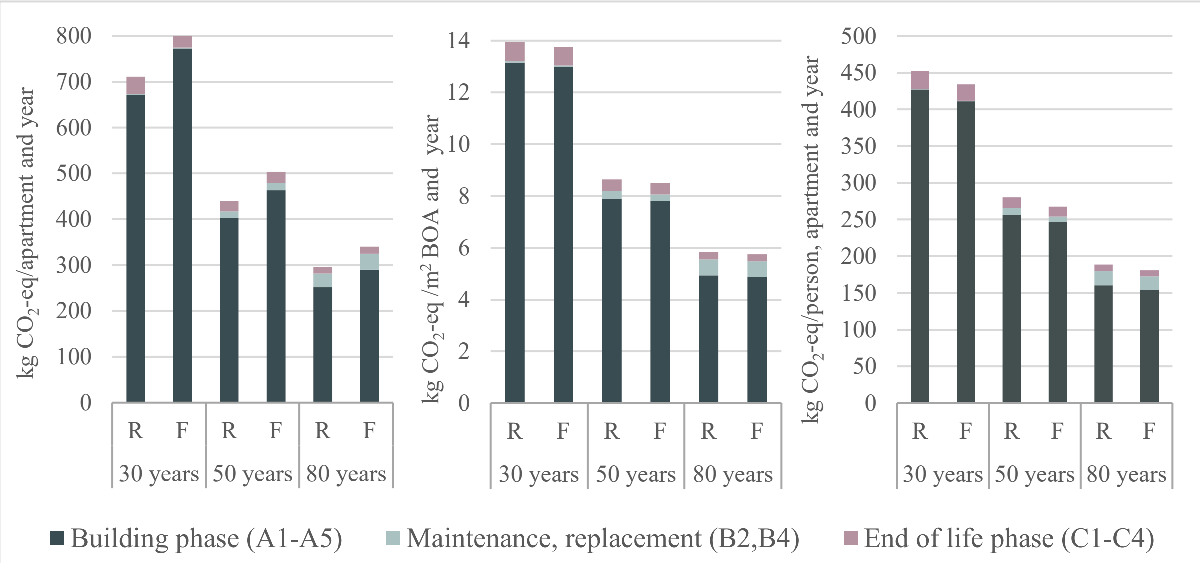


Figure 18 The impact in kg CO_2-eq distributed by life cycle phase for one life cycle. For the functional units apartment and year, m^2 BOA and year and person, apartment and year and the reference study period 30, 50 and 80 years. R-reference case, F-flexible case.

6.7.2 The impact when considering two life cycles

Figure 19 and 20 show the impact over two life cycles according to the scenarios described in Section 6.4.2. As oppose to Figure 13, they are here presented *per* lifecycle and for different reference study periods. When considering several connected systems, the impacts need to be allocated (Eberhardt et al., 2019). This means that the impact of the flexible case needs to be allocated between the two cycles in order to make an assessment *per* life cycle or *per* product/building. This is done in two different ways in Figure 19 and 20, and is meant to showcase how design for flexibility is differently promoted depending on how impacts and benefits are allocated.

As already shown in Figure 13, it is clear that the flexible case has a lower climate impact than the reference case if considering two life cycles. The main reason for this is seemingly that the concrete structure, particularly the floors, walls and foundation stand for the biggest share of the climate impact of the building phase, see Figure 14. Thus, prolonging the service life of these components is very beneficial.

Table 26 shows the impact reduction obtained with the defined functional units, refurbishment scenarios and reference study periods. The flexible case obtains a climate impact reduction of 21-49%. Highest climate reduction can be observed when using the functional unit *person, apartment and year* and a reference study period of 30 years. The lowest impact reduction can be observed when using the functional unit *apartment and year* for a reference study period of 50 years. The reason why it is lowest for 50 years might be due to an increased number of elements requiring replacement after 50-60 years, see Table 19. Looking at Figure 15, it is clear that the impact is considerably larger for a period of 100 years (accounted for in the flexible case) than for 2 x50 years (accounted for in the reference case). Even though not explicit from Table 26, it can be expected that the impact reduction of the flexible case decreases the longer the reference period, because of the higher need for interventions due to more building elements having reached the end of their service life.

Table 26 Climate impact (kg CO_2-eq) reduction of the flexible case (refurbishment scenario F1-F3) compared to the reference case considering two life cycles. For the functional units apartment and year, m² BOA and year and person, apartment and year and the reference study period 30, 50 and 80 years.

Functional unit	**Climate impact reduction [%]**									
	30 years			**50 years**			**80 years**			
	F1	F2	F3	F1	F2	F3	F1	F2	F3	
Apartment and year	39	36	26	33	30	21	35	33	24	
m² BOA and year	47	44	36	42	39	31	44	41	34	20-30
Person, apartment and year	49	47	39	44	42	34	46	44	36	30-40 40-50

6.7.2.1 Allocation approach 1

In Figure 19, the first life cycle of the flexible case takes the burden of the building- and use phase of the first cycle, while the second life cycle takes the burden for refurbishment, use phase of the second cycle and end of life phase. This aims to resonate with the methodology of EN 15978 where a refurbishment entailing new or upgraded functions (at least that wasn't anticipated from the start) should mean a new analysis period, and so a new LCA should be considered (Erlandsson & Holm, 2015; SIS, 2011). This approach can also be resembled with the cut off approach (Bauman & Tillman, 2004). The cut off approach is an allocation method to handle so called open loop recycling, where each cycle (or product) is responsible for the impact directly caused by that cycle. Thus, looking at two life cycles, the raw material production is allocated to the first cycle, whilst the process of reuse or recycle and waste management is allocated to the second. This allocation approach means that the first cycle is freed from burdens of end of life, thus promoting multiple use cycles in that way.

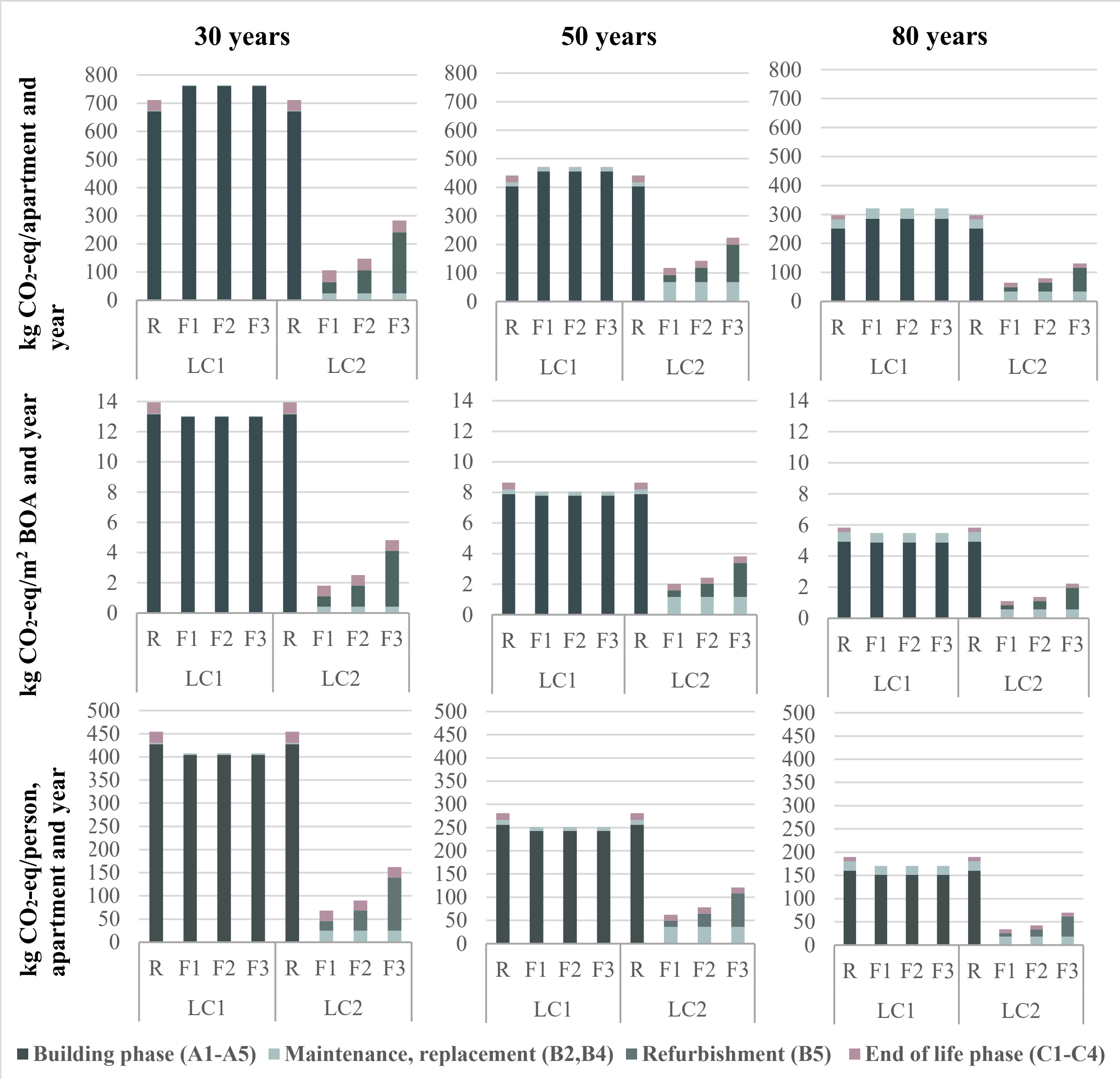


Figure 19 *The impact in kg CO_2-eq over two life cycles with allocation approach 1. For the functional units apartment and year, m^2 BOA and year and person, apartment and year and for the reference study periods 30, 50 and 80 years. R-reference case, F1-flexible case scenario 1, F2-flexible case scenario 2, F3-flexible case scenario 3. LC1- life cycle 1, LC2- life cycle 2.*

6.7.2.2 Allocation approach 2

In Figure 20, all impacts, expect of the use phase, are distributed equally between the life cycles of the flexible case. By splitting impacts and benefits between the number of life cycles, one is not benefited over the other. This allocation method is meant to benefit the first life cycle since the building is designed in a way that enables a second life cycle. In this way it promotes design for multiple life cycles, much more than allocation approach 1. From the literature review it was discovered that this is a method to credit multiple life cycles in an

LCA (Eberhardt et al., 2019; Tingley & Davison, 2012). This allocation approach clearly shows the benefit of the flexible case, however there are obvious challenges in benefiting the first life cycle or building with occurrences in a future uncertain life cycle.

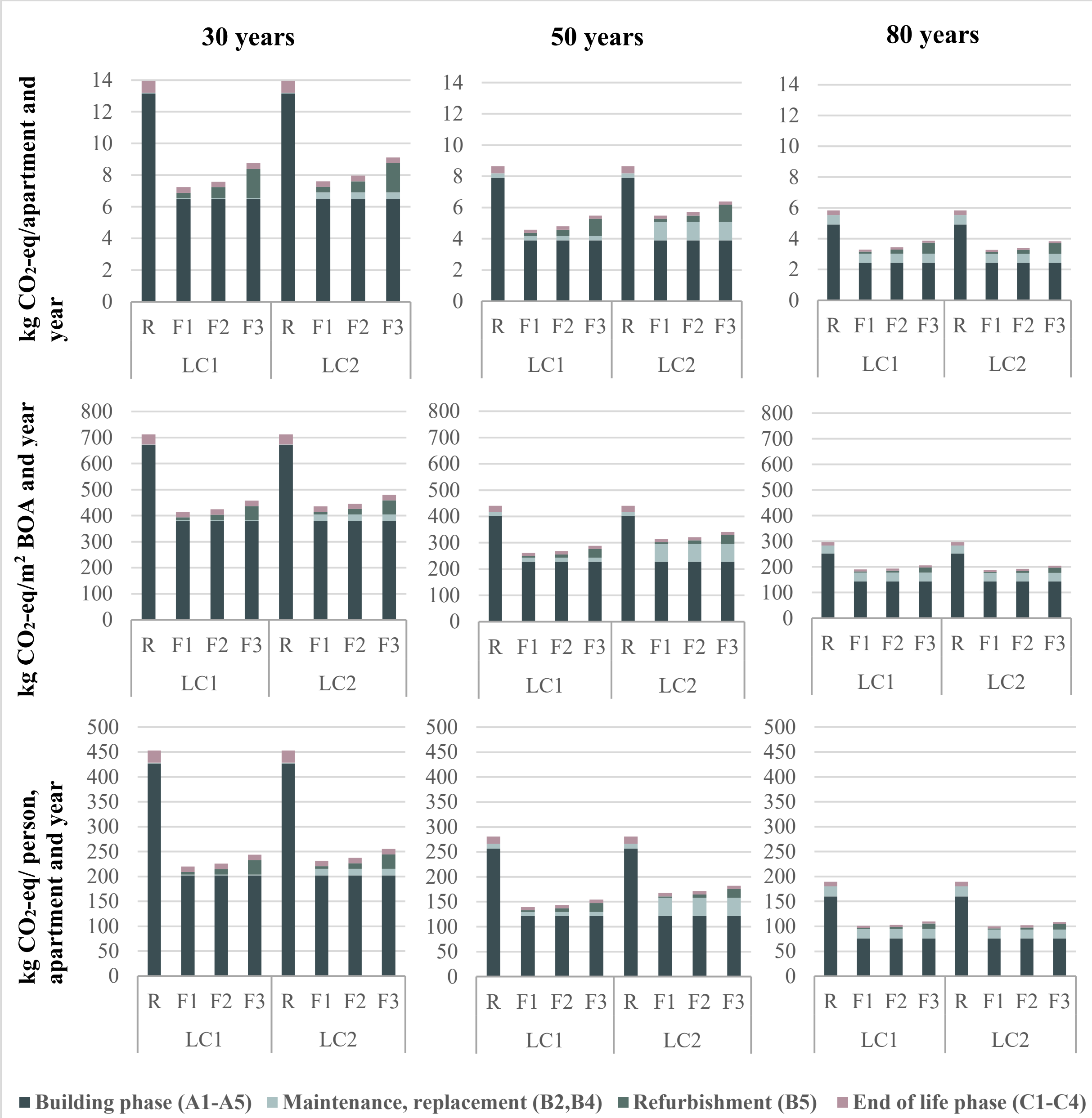


Figure 20 *The impact in kg CO_2-eq over two life cycles with allocation approach 2. For the functional units apartment and year, m^2 BOA and year and person, apartment and year and for the reference study periods 30, 50 and 80 years. R-reference case, F1-flexible case scenario 1, F2-flexible case scenario 2, F3-flexible case scenario 3. LC1- life cycle 1, LC2- life cycle 2.*

6.7.3 Comparison with other studies

The results of the case study are compared to other studies in order to verify its reliability and relate to the different parts of this thesis.

6.7.3.1 Comparison with another multi-family residential building

The result of the impact assessment is compared to another multi-family residential building with a load bearing structure in concrete called Blå Jungfrun. The values shown in Table 27 are from a report by Liljenström et al. (2015) and are adapted to the functional unit *m^2 BTA* instead of $m^2\ A_{temp}$. The values of Varvsporten are shown without limitation of building parts (as given by the pre-existing report) as well as with (the reference case and the flexible case). No limitation of building parts means that installations/services, inner surfaces and the groundwork is included in the study beyond the ones listed in Table 14. This represents a more equal comparison to the LCA of Blå Jungfrun, which includes a similar amount of building parts. For the sake of comparison, the values of the flexible case are also adapted to the functional unit *m^2 BTA* which includes the assumption that the relationship BOA/BTA is the same for the two cases.

The largest difference is from module B2, B4 where the value of Blå Jungfrun is considerably higher. According to a similar study by Larsson et al. (2016) the largest contribution to B2 and B4 comes from the replacement of services/installations such as the elevator and floor heating system. Since the case study does not include services/installations this could be a possible reason why the impact becomes small.

Table 27 Climate impact (kg CO_2-eq/m^2 BTA) for Blå Jungfrun and Varvsporten.

Life cycle phase	**Blå Jungfrun (kg CO_2-eq/m^2 BTA)**	**Varvsporten (kg CO_2-eq/m^2 BTA)**		
		No building limitation	**Reference case**	**Flexible case**
A1-A5	336	350	294	296
B2, B4 (50 years)	58	-	11	10
C1-C4	22	-	17	16

6.7.3.2 Comparison with the literature review and qualitative assessment

The case study indicates comparable results to the literature review and the qualitative assessment. Similar to the qualitative assessment, if assessed per apartment, the design strategies *functionally neutral rooms* and *increased floor height* mean a potential decrease of climate impact in a long-term perspective, with an increase of in the building phase. The case study shows that a potential increase in the building phase can be 13 % if using a functional unit of *apartment and year*. While a decrease from going from one to two life cycles ranges from 30-40% resulting in a total impact reduction between 21-33 % for a reference study period of 50 years and depending on refurbishment scenario.

Compared to the qualitative assessment, the benefits obtained in a refurbishment by design for flexibility is not explored in the case study as only the flexible case goes through refurbishment, but as Rasmussen et al. (2020) showed a decrease can be expected if both cases are refurbished to attain similar changes.

Although results depend a lot on for instance methodological assumptions and design strategies some results from the studies of the literature review, see Table 7 and Section 4.2.4, are compared to the case study. Eberhard et al. (2019) get an impact reduction from using the concrete structure two times with a reference study period of 50 years and functional unit of *m^2 BTA and year* to be 18 %. Comparing to the case study, scenario F3 and functional unit *m^2 BOA and year* is most compatible which gives an impact reduction of 31 %, see Table 26. However, the study by Eberhardt et al. (2019) assess reusing building parts and not the whole building and further the study shows a large variety depending on building composition, ranging from 18 to 49 %. Similar to Eberhardt (2019) the concrete structure, and especially the floor is the dominant contributor to the climate impact, resulting in large benefits gained from reusing it. Marsh (2017) obtains an impact reduction from changing the lifespan from 50 to 80 years to 29 % and in the case study the same change obtains a 33 % reduction, see Figure 18. In the study by Bastos et al. (2014) the larger apartment has a smaller impact with an area based functional unit and the space efficient (smaller apartment) has a smaller impact with an occupancy based functional unit. The same trend was found in the case study, where the flexible case, with the larger area, looks better with an area based functional unit compared to an apartment based functional unit. Furthermore, an occupancy based functional unit makes the flexible case look better, because of the increased space efficiency obtained.

7 Analysis and discussion

In this chapter an analysis of the result is made. It is structured according to the research questions and thus firstly focuses on what design for flexibility is and can imply, then methodological choices of LCAs to account for it and then the climate benefit it entails. Lastly chosen research methods and consequences of limitations of the study are discussed.

7.1 Design for flexibility

The literature review revealed that design for flexibility is a rather broad definition, with varying terminology and many design strategies. Three categories of flexibility were distinguished with relevance to a life cycle perspective. The first category *flexibility in social use* involves designing buildings that don't depend on material flows to adapt to other functions and uses. The second category *flexibility in physical use* involves bedding for the ability to adapt through material flows, or in other words bedding for refurbishment instead of demolition and rebuilding. The third category *flexibility in material/ technical use* involves designing the structural and material composition in a way so that components can be replaced, reused and recycled. The three categories serve different yet, according to the literature, similarly important purposes. The benefits range from short-term to long-term and from a material to an urban level. The first category allows quick and impermanent changes, which means that spaces can be shared and the use and function can easily shift. This means that the building is potentially used efficiently and its value kept high longer. The second category gives benefits similar to the first, but instead of minimizing physical change it allows it. This notion is interesting as the permission of physical change in theory means that permanence is formed. The second and third categories becomes extra relevant if considering reaching climate goals. A Swedish goal is to be climate neutral by 2045 (Fossilfritt Sverige, 2018). This supposedly means that buildings not just need to be built climate neutrally today but that the existing stock also needs to adapt to new, efficient technology. Furthermore, one can wonder if it is not necessary that future building practice minimizes the use of virgin materials, meaning that making use of the existing will be obligatory. This ultimately means that reaching climate goals can be aided by allowing for the buildings we make today to adapt to developments within sustainability yet to happen.

The design strategies found in literature could be grouped into *geometry and plan* and *material and services*. Two interesting analysis can be made of these; the first is that *geometry and plan* is perhaps more related to early design strategies and thus needs to be considered from the very start of the design process. The second is that, seemingly, *material and services* are slightly more commonly (and perhaps more easily) assessed in LCAs.

The literature review further points to two important analysis to be made. The first relates to the importance of designing for flexibility and the many design strategies that as a consequence have been formed. The second relates to the lack of and difficulty to make assessments. The latter is due to a subjective and qualitative side to flexibility and to the uncertain nature of it. The uncertainty can be viewed in two ways; one is whether the benefits will be delivered or if the actual employment of flexibility will never happen. The other is, if employed, which direction will it go?

7.2 LCA and methodological choices

In the literature review, methodological choices of LCAs were examined. Firstly, recommended ones and then of LCAs assessing design for flexibility and related strategies. Then, in the qualitative assessment and case study, methodological choices were applied which gave further insight to how design for flexibility can be accounted for in an LCA. Three methodological choices stood out as significant and are analysed further, *functional unit*, *reference study period* and *multiple life cycles and allocation*.

7.2.1 Functional unit

The Functional unit is meant to represent the function of object of the LCA and give a reference flow to which all impacts are related to and thus be a basis for comparison. However, because buildings are very multifunctional it is not always easy to assign one. In the literature review functional units used varied from being based on square meter, person to whole building although recommended functional units were found to be square meter based. From the literature review it was also found that LCA results comparing buildings can vary depending on choice of functional unit. Therefore, three functional units were chosen for the case study; an area based, an occupancy based and one representing the apartment. The case study showed, similar to the literature review, that the choice affected the results. For instance, an area based functional unit seems to potentially benefit larger buildings/apartments over smaller. An occupancy based functional unit favours high density but may introduce a risk of compensating for lack of environmental performance (Bastos et al., 2013). Therefor this study indicates that using several functional units might be preferable. The case study further hints that choosing functional unit is a sensitive matter due to multifunctionality. It compares two cases of one apartment, one where the original design is altered to create flexibility. This means that the functions of the cases are in fact different. Furthermore, the case study includes a hypothetical future change of function in the form of refurbishment or demolition/rebuilding and then the functional unit may no longer be relevant. This introduces some hindrance to comparison despite the use of more than one functional unit.

Moreover, if considering flexibility not only on a building scale, but also on an urban scale, where spaces and services are shared beyond the limit of one building, the question can be asked if m^2, person, building, or city is the right measurement to rightly evaluate resource efficiency (the footprint).

7.2.2 Reference study period

In the literature review it was found that a reference study period of 50 years is commonly applied and recommended. However, LCAs assessing design strategies related to flexibility generally use several or longer periods. Reasons for this include that longer service lives are predicted, uncertainty of the service life, and the effect it has on the size of the use phase. The choice of 50 years may not be illogical; it reflects a common required service life of many building parts and a period where one building function can be expected to be relevant, because after 50 years refurbishment might be expected to upgrade or change the building function (Erlandsson & Holm, 2015). However, a reference study period of up to 50 years generally doesn't include the limit where the building is not fit for purpose anymore and will either be demolished or considered for refurbishment. This perhaps means that less or no regard is taken to if the building can pass the test of obsolescence.

7.2.3 Multiple life cycles and allocation

One way to include the limit of weather the building passes the test of obsolescence or not seems to be by accounting for subsequent systems. In the case study a multiple life cycle approach is investigated. From the literature review it was found that this is a way to account for circular building design (Eberhardt et al., 2019), which arguably flexibility fits well into.

Another way to account for benefits of later life cycles is to include module D in the LCA. According to EN 15978, module D reports the benefits from reuse, recycle and energy recovery, and should be reported separately in the LCA (SIS, 2011). This method assigns all impacts and benefits to the first life cycle, and thus not to other life cycles. However, the literature review implies that this can be a way to account for using a building beyond the first life cycle, and reporting it separately means that the risk of accounting for benefits that don't occur is less profound. How to apply this on design for flexibility was however not further examined in this thesis, and in reviewed literature it is only applied to components that are reused or recycled rather than whole buildings. Also, comparing to recommended methodological choices the certification system NollCO2 doesn't include module D and for starters the mandatory climate declarations will only include modules A1-A5. This means that building for reuse will not earn any benefits if doing the LCA for one of these purposes. An important further study to be made could therefore be of the importance to include module D.

This study however, indicates that focusing on how life cycles are connected and shifting from one to multiple life cycles is an interesting concept if moving to a more circular building practice. This study implies that if an LCA only considers the time from when a building is built to the time it is demolished or rebuilt (which may be expected after 50 years or so) then refurbishing, reusing and prolonging instead of demolishing might not be fully valued. A further speculation related to the building layers by Brand (1994) that can be made is; what would happen if the LCA would shift from being restrained to the building, to instead bound to the site?

The allocation method is found to be important when considering systems that proceed each other. Allocating all impacts and benefits to the first cycle, means multiple systems will not be included, however allocating to another lifecycle risks that no system actually takes the burden if not utilized (Eberhardt et al., 2019). Therefor it is not an obvious method. From the literature review it was found that many allocation methods exist and can affect the results a lot (Minunno et al., 2020; Eberhardt et al., 2019; Collins et al., 2010). For instance, the allocation method determines what benefits are obtained in the LCA from reusing materials or bedding for future reuse, and the literature review indicated that building with reused materials often is more beneficial than building with materials that can be reused. In the case study, two allocation methods were tested to assign benefits and impacts to the two life cycles. Firstly, the cut off approach was followed, meaning direct burdens are assigned to each life cycle (Baumann &Tillman, 2004). Consequently, the first building life cycle was burdened with building and use phase whilst the second life cycle was burdened with refurbishment, use phase and end of life. The second approach instead allocated the impacts of the building phase, refurbishment and end of life equally between the life cycles. Consequently, when assessing per life cycle or per building, the allocation method affected the results to a great deal. Both allocation methods were shown to encourage design for flexibility but the second approach to a larger degree. The logic for the cut off approach is reasonable, as benefits supplied in the future are not certain. Further it benefits building with recycled materials, which is an essential strategy if considering the importance of abating emissions now. However, it also means that design strategies that bed for ease of reuse are not largely benefited.

7.2.4 Challenges of incorporating design for flexibility in an LCA

This thesis indicates that there are many challenges when assessing design for flexibility in an LCA. It includes assessing qualities that are both hard to measure and uncertain. This might be one of the reasons why, as discussed by Malmqvist et al. (2018), material strategies such as wooden compared to concrete structures are more commonly assessed than strategies such as flexibility, which according to this study is very scarce. Even regarding flexibility, design strategies connected to *material and services* were found to be assessed to a higher degree. It was found that commonly applied calculation methods need to be adapted to account for design for flexibility. Furthermore, the case study revealed some challenges when following the ISO framework, see Section 2.1.1, in presenting the LCA in a clear way, especially when considering two life cycles.

There lies a challenge in that qualities that are harder to measure might be underprioritized. As described by Meadows (1998) "not only do we measure what we value, we also come to value what we measure" (p. 2). Thus, the more quantitative measurements are required in the building sector, for instance through the climate declarations required by Boverket as of 2022, maybe the more risk there is that long-term qualities that are hard to measure are at stake.

7.3 Climate benefits of design for flexibility

This section discusses what climate benefits flexibility offers according to this thesis as well as the implications methodological choices had on the results.

7.3.1 Climate benefits according to the qualitative assessment

The qualitative assessment shows that a wide range of design strategies for flexibility can give climate impact reductions. It indicates that most of the assessed design strategies enable a potential decrease in later life cycle stages. Some design strategies mean an increase in the building phase (the cradle to gate impact) due to the need for higher material use. However, several indicate no significant increase in the building phase making these particularly interesting. Some strategies that enable *flexibility in social use*, also indicate the need for less material use, meaning a decrease in the building phase. The qualitative assessment shows that the life cycle perspective is important when considering flexibility and if only cradle to gate impacts are assessed, then design strategies offering important reduction potential might be missed.

7.3.2 Climate benefits according to the case study

The case study, comparing a reference case to a flexible case, shows that large climate benefits can be obtained from a longer lifespan and increased space efficiency. Two life cycles are considered, where the reference case is demolished and rebuilt after the first cycle and the flexible case is refurbished and thus kept for two life cycles. On this foundation the case study indicates that a building designed for flexibility, and for this reason has a second life cycle beyond the first, can have a climate impact that is 21-49% lower than a building not designed for flexibility. The span obtained is due to methodological choices (functional unit, reference study period and choice of scenario) and illustrates the influence that methodological choices have on an LCA. The benefit from going from one to two lifecycles alone is 30-40% for a reference study period of 50 years and depending on refurbishment scenario. Thus, it is also shown that refurbishment is preferable to demolition and rebuilding.

The result also points to the benefits obtained by increasing the building lifespan. Compared to 30 years, 50 years gives an impact that is 38% lower and 80 years that is 58% lower. However, the advantage was shown to decrease slightly the longer it is, due to larger impacts from the use phase. This trend was smaller than expected though, partly because the impact for maintenance and replacement was small when comparing to another LCA, due to exclusion of building parts and particularly installations. Further, including more modules of the use phase, especially energy use, would have decreased the benefit of extending the lifespan shown by Marsh (2017) and Liljenström et el. (2015). Therefore, disadvantages of prolonging the building lifespan (both through a second life cycle and longer reference study period) is not entirely regarded in the case study. Also, at some point the building might reach the level of obsolescence where a refurbishment will neither be economically nor (maybe) environmentally preferable.

Results were also obtained considering a scenario where only one life cycle of both cases occurs. This reflects a common LCA where only one life cycle is included. The results were interestingly found to depend on the choice of functional unit. With a functional unit of *apartment and year*, the flexible case has a 14 % higher impact but with *m^2 and year* the impact of the flexible and reference case is similar. Further with a functional unit of *person and year* the trend is reversed and the impact of the flexible case is smaller for all life cycle phases with a total decrease of 4 %. This makes the results somewhat ambiguous and like already discussed the choice of functional unit is not obvious. Comparing per apartment may seem fair as an increased material flow logically should give a higher impact. However, as previously discussed, this means that different functions are compared which in itself is unfair.

The case study shows, similar to the literature review, that the load bearing concrete structure, and especially the floor slabs, make the biggest contribution to the climate impact, mainly in the building phase as this phase is dominant but also to the end of life phase. The case study firstly indicates the importance of limiting the embodied material use, by showing that an increased floor area of 15 % and an increased floor height of 8 % of an apartment increases the cradle to gate impact by 13 % assessed per apartment. However, the case study also shows the importance of prolonging, reusing and using more. If considering the layers defined by Brand (1997), see Figure 3, the structure is (after the site) the most long-lived part of a building, with a low rate of change. In the case study this is exemplified by that the use phase is the only phase where concrete is not the dominant contributor. All in all, with a life cycle perspective, the largest benefits are, according to the case study, obtained by prolonging the life of the concrete elements despite a possible initial increase.

7.3.2.1 The scenarios of the case study

The case study was made to assess the potential climate impact reduction of design for flexibility. But it was also formed to compare “known” initial increase to potential decrease. In doing this, several questions are shaped regarding impacts now and at a later time and how to incorporate values that bed for, plausible, but not certain benefits. Scenarios introduce a big uncertainty, firstly identified from the literature review and qualitative assessment and then tested in the case study. There exists lack of guidance on how to make scenarios and often they differ between studies (Malmqvist et al., 2018; Rasmussen et al., 2020; Lowres & Hobbs, 2017). The qualitative assessment illustrates that most benefits of design for flexibility are scenario based. The scenarios of the case study focused on longevity (modelled as the number of use cycles) and occupancy of the reference and flexible case. Firstly, it was assumed that the reference case has a longer lifespan than the reference case and secondly that an increased use is created increasing the occupancy on average during the lifespan. These assumptions are grounded in previous research, literature and conversations with architects. They are based on physical design actions which as oppose to merely making scenarios of future performance makes an important distinction as discussed by Malmqvist et al. (2018). Yet, the uncertain nature of the scenarios obscures the results, as they depend on flexibility being employed. In reality, even if flexibility is invested, it is nearly impossible to guarantee it. For instance, it is discussed in literature that there often needs to exist clear information on the flexible capacity that exists (Braide, 2019). Further it is often dependent on decisions made by future designers, occupiers and building owners (Malmqvist et al., 2018). Interesting might therefore be, to consider the design strategies defined in this thesis that don't lead to an increased cradle to gate climate impact. Several of these strategies were included in the qualitative assessment ranging from geometrical regularity of floor plans, careful placement of the service core, non-load bearing inner walls and design for disassembly.

It is important to consider what could reduce the uncertainty of flexibility being employed. If it is cheaper to tear down a building and build a new one than to rebuild and preserve then an important question is what other values makes us want to preserve a building? Also, maybe another economic model where the circular one is benefited is needed?

An issue with long-term, scenario-based qualities is that an investor might not be willing to pay for it. Therefore, making it quantifiable, more plausible, and less ambiguous is an important task. Flexibility can give long-term values despite socioeconomic fluctuations by increased use per m^2, decreased cost from adaptations, longer lifespan and minimized risk of becoming prematurely obsolete (Slaughter, 2001; Fawcett, 2011). Yet there remains a challenge if short-term profits are prioritized, where compact housing with low quality materials is sometimes preferred and where the actual user may be benefited the least.

7.4 Limitations and consequences of chosen methods

In this section limitations and consequences of methods applied in this study are discussed.

7.4.1 Mixed methods approach

The study consists of a literature review, qualitative assessment and a case study. A gain from using a mixed methods research approach is that the question is answered from both a qualitative and quantitative viewpoint, which also means that the shortcomings from using either are limited (Creswell, 2014). However, challenges that have been experienced is time demand along with a risk that neither is given the in-depth focus needed. Still, the aim of the literature review and qualitative assessment was to give a broader insight whilst the aim of the case study was to give a tangible, yet more narrow measurement, which the author feels has benefited the study.

7.4.2 Overall limitations

The most obvious limitation of the qualitative assessment is its lack for quantitative results. Further it is not assessed with a functional unit in mind which both gives somewhat inconclusive results and makes it hard to compare to the case study. Also, the studies it is largely based on uses a mix of methodological choices, which has shown to affect results. For the literature review and the qualitative assessment, the limited number of reviewed studies might have affected the results. Further, there may exist a gap between literature and what in practice is the "best way to go" with regards to flexibility. It was found that there is a general lack of assessments of design for flexibility. Therefore, much literature has a subjective approach as is often the case with architectural design. Consequently, the qualitative assessment is to a large extent based on judgment and not previous LCAs. Nonetheless, the qualitative assessment contributes with a holistic perspective made faster than a quantitative LCA and offers a way to assess design strategies that are hard to quantify.

Although not included in the scope of the thesis, flexibility offers other values than environmental benefits, for instance contributions to social sustainability (Braide, 2019; Schneider & Till, 2007). The qualitative assessment nor the case study assess to what degree design for flexibility performs better with regards to for example health and safety. However, the discussions made on the design alterations in the case study, gave indication to the increased social values attained, where the value of choice, safety and power came up.

Furthermore, no consideration to other impact categories than climate change is taken in the qualitative assessment nor case study. This would likely have changed the magnitude of benefits and impacts. For instance, the impact category land use could assumably be of relevance when space efficiency is discussed.

7.4.3 Limitation of the case study

Not all life cycle modules according to the standard EN 15978 have been included, such as energy use. Energy use usually stands for a substantial part of the life cycle impact and is further dependent on the reference study period. Also, not all building parts are included, such as services/installations. The impact of the use phase is low, partly due to these limitations.

The choice of data can have affected the result of the case study. Mostly generic data were used and from both Ecoinvent's and BM's climate database. Most data from Ecoinvent are based on Swiss or European data, while the data from BM represent Swedish average. Further, if data were not found for a material, data for similar materials were chosen. Also, version 3.2 of Ecoinvent was used which is not the latest version, the reason being lack of data availability. Although this introduces uncertainty to results, they are assumably small and the purpose of the LCA is still regarded as fulfilled.

The case study limits to one apartment type of Varvsporten and in doing so makes assumptions on how the total climate impact can be assigned to that apartment and how material quantities change with design alterations. It does therefore not take into account changes to other apartments and other spaces like staircases and corridors. Furthermore, the results are presented per apartment and are dependent on the floor plan employed in the study. Had another design been made, the results would most likely have been different. It further only considers a few design strategies, and these are related to *geometry and plan,* thus *material and services* is not assessed. The limit to few design strategies means that the case study does not assess *decreased climate impact from maintenance, repair, replacement, refurbishment and end of life* nor *improved lifecycle performance*. Nor does it assess the benefit of *efficient use of space* from creating smaller multifunctional apartments. It is also interesting to note that had another building been chosen for the case study, then the results might have altered. For example, this includes a wooden as oppose to the concrete structure.

The case study does thereby not give a universal answer to the climate benefit of design for flexibility. Nonetheless, the aim of the case study, to explore its possible climate benefit, is regarded as fulfilled. It has furthermore explored what challenges exist when accounting for design strategies such as flexibility in LCAs and how it potentially can be tackled.

7.4.4 Static vs dynamic LCA

The LCA of this thesis is conducted using a static approach, meaning that dynamic aspects of the building are not included. The alternative would be to perform a so called dynamic LCA, described in Section 2.1.3, but due to lack of time and because the application of it is out of the scope of this thesis it is excluded from the study. Nevertheless, it is important to note that this introduces limitations to the results.

Because design for flexibility is concerned with accommodating and responding to changes, a dynamic LCA could provide more realistic scenarios. This could guide the design in the right direction as well as assess it with higher confidence. Some parameters that could have been looked at from a dynamic approach are:

- ***Technological progress***. In the case study components are assumed to be exchanged with the same components and the energy mix, production efficiency and waste handling is based on current practice. Considering technological progress means impacts for producing new material or waste handling of old materials would change and thus the relationship between prolonging the lifespan of building components or producing new would change. For instance, the fuel mix and efficiency of future energy upstream processes or materials for new buildings or replacement could have been considered.
- ***Usage patterns***. The user is naturally central to a residential building. By considering the change in how buildings are used the idea of flexibility becomes perhaps more pragmatic. The way buildings are used today differs from how they were used a few decades ago (König et al., 2010), and probably will be different in a few decades. Usage patterns can give an indication of the need for change and what kind is required. For instance, if densification is required due to demographic movements the ability to add stories is valuable. Or perhaps living and working constellations will change making the ability to change these spaces valuable.
- ***Characterization factors***. The case study partially weighs initial cradle to gate climate impacts to values in later life cycle phases. By considering dynamic characterization factors, the impacts caused today can possibly be more accurately compared to impacts occurring in the future, including factors such as tipping points and resource scarcity.

However, all these parameters are very uncertain, as buildings have a long and complicated development path. Furthermore, data on future processes is often very hard to retrieve (Collinge et al., 2013). Nonetheless, considering a range of scenarios in a dynamic LCA can give important indications of trade-offs to be made at the early design phase (Collinge et al., 2013).

7.4.5 General analysis on LCA of flexibility?

Because the values of design for flexibility are, similar to many design strategies, not easy to measure, there are limitations to the obtained results of this study. The indications it makes can however hopefully be applied to other contexts. Design for flexibility is shown to potentially give many climate benefits that according to this study seemingly makes it necessary. A holistic life cycle perspective has been shown to be important. Meaning attention should be paid to methodological choices of LCAs, but also that flexibility should not be applied in isolation but that the early design should incorporate many perspectives.

8 Conclusions

This thesis studies the life cycle performance, with a focus on climate impact, of design for flexibility in multi-family housing. It also investigates how LCA can be used to evaluate the design. It presents a literature review identifying design for flexibility, a qualitative assessment evaluating design strategies commonly mentioned in the literature review and lastly a case study with an LCA comparing a reference and flexible case, the latter assigned design strategies for flexibility.

The literature review identifies three categories of flexibility in relation to a life cycle perspective; flexibility without physical alterations to space, by the means of physical alterations to space and by making physical change to the material and technical composition. A large variety of design strategies are identified along with environmental benefits to be obtained, namely extended lifespan, increased space efficiency, decreased impact from use and end of life phase and increased lifecycle performance. It further identifies a lack of existing LCAs of design strategies such as flexibility, a lack of unified LCA methods and a need to adapt commonly applied calculation methods to account for flexibility. The study shows that methodological choices of an LCA that can account for flexibility are for instance; considering multiple life cycles, extending the reference study period and using an occupancy as well as an area based functional unit.

The qualitative assessment identifies that benefits can be obtained on a short but especially on a long-term basis. Several design strategies that give long-term benefits indicate no increase of impact in the building phase and some do. Furthermore, most benefits are scenario based.

The case study suggests that design for flexibility, that will enable an extended lifespan and space efficiency, can imply a climate impact reduction of 21-49% depending on methodological choices. An area, occupancy and apartment based functional unit, three reference study periods, refurbishment scenarios and two life cycles are included. When considering two life cycles, the allocation of impacts and benefits between them is shown to affect to what degree flexibility as a design choice is promoted. According to the case study, reducing the initial climate impact is important but prolonging, reusing and using the long-lived parts of a building more can have even larger benefits. However, these benefits are also scenario based. This introduces challenges in an LCA, as qualities to be quantified are both hard to measure and uncertain, which also gives limitations in generalising some results of this study.

Design for flexibility is in many ways hindered due to uncertain future manifestations. Yet, one of the most essential reasons for it is that the future is, and undoubtfully so, uncertain.

Future research could conduct LCAs of additional design strategies for flexibility. Research on what makes flexibility employed or not could also be an important field of exploration. Further, dynamic LCAs and more scenarios to cover the sensitivity of the future is an important task. Lastly, other values than climate impact could be taken into account and an environmental LCA could be accompanied by a social (SLCA) or economic LCA (LCC).

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Appendix I- Inventory: Data of the case study

Building phase (module A1-A5)

A1-A5	*Reference case*					*Flexible case*					*comment*
	Quantity	*Impact*				*Quantity*	*Impact*				
	kg	*kg CO2 eq*	*kg CO2 eq/BTA*	*kg CO2 eq/BOA*	*kg CO2 eq/ apartment*	*kg*	*kg CO2 eq*	*kg CO2 eq/BTA*	*kg CO2 eq/BOA*	*kg CO2 eq/ apartment*	
Load bearing structure											
A1-A3											
Walls											
Concrete (C28/35 vct 0,55 4/8 mm)	1492788,15	185105,73	21,07	28,28	1442,16	1508700,72	201596,69	20,00	26,84	1570,64	
Reinforcement	5694,00	3299,40	0,38	0,50	25,71	5754,70	3593,35	0,36	0,48	28,00	
Plywood	1897,00	387,45	0,04	0,06	3,02	1917,22	421,97	0,04	0,06	3,29	
Glass wool	1558,08	1947,60	0,22	0,30	15,17	1574,69	2121,11	0,21	0,28	16,53	
Prefabricated concrete walls	1242480,00	228616,32	26,02	34,92	1781,15	1255724,38	248983,61	24,70	33,15	1939,84	
Floors											
Conrete (C35/45 vct 0,50 8/11)/(C28/35 vct 0,5	4040829,70	525307,86	59,79	80,25	4092,68	4646954,16	604104,04	59,92	80,43	4706,59	
Prefabricated concrete slabs	920824,00	169431,62	19,28	25,88	1320,04	1058947,60	194846,36	19,33	25,94	1518,05	
Balcony /balcony access	380700,00	49491,00	5,63	7,56	385,59	401850,00	52240,50	5,95	7,98	407,01	*estimated from floor plan drawings*
Steel studs	157,89	383,21	0,04	0,06	2,99	181,58	440,69	0,04	0,06	3,43	
Reinforcement	100523,54	58248,66	6,63	8,90	453,82	115602,07	66985,96	6,64	8,92	521,89	
Plywood	16,80	3,43	0,00	0,00	0,03	19,32	3,95	0,00	0,00	0,03	
Gypsum boards (fire)	681,12	257,46	0,03	0,04	2,01	783,29	296,08	0,03	0,04	2,31	
Glass wool	886,59	1108,24	0,13	0,17	8,63	1019,58	1274,47	0,13	0,17	9,93	
Gypsum boards without carton	97,37	26,46	0,00	0,00	0,21	111,98	30,42	0,00	0,00	0,24	
Clay aggregated blocks	10880,00	2502,40	0,28	0,38	19,50	12512,00	2877,76	0,29	0,38	22,42	
Studs											
Reinforcement	2200,00	1274,80	0,15	0,19	9,93	2530,00	1466,02	0,15	0,20	11,42	
Staircase	42000,00	8778,00	1,00	1,34	68,39	48300,00	10094,70	1,00	1,34	78,65	
Construction steel	43400,00	74300,80	8,46	11,35	578,88	49910,00	85445,92	8,48	11,38	665,71	
A4 Transport		158373,05	18,03	24,19	1233,89		177377,81	17,38	23,32	1364,87	
Room forming elements											
A1-A3											
Inner walls											
Plywood	6533,12	1334,35	0,15	0,20	10,40	8254,17	1685,87	0,17	0,22	13,13	
Gypsum boards with carton	116087,44	31540,96	3,59	4,82	245,74	146668,98	39849,96	3,95	5,31	310,47	
Glass wool	8393,45	10491,81	1,19	1,60	81,74	10604,58	13255,73	1,31	1,76	103,28	
Gypsum boards without carton	36102,88	9809,15	1,12	1,50	76,42	45613,65	12393,23	1,23	1,65	96,56	
Steel studs	25652,43	62258,45	7,09	9,51	485,06	32410,19	78659,52	7,80	10,47	612,84	
Transport		7042,12	0,80	1,08	54,87		8897,26	0,88	1,18	69,32	
Facade											
A1-A3											
Curtain wall											
plywood	574,20	117,28	0,01	0,02	0,91	812,80	119,86	0,02	0,02	1,29	
Sealing strip	375,40	1448,91	0,16	0,22	11,29	531,39	1480,83	0,20	0,27	15,98	
Gypsum boards without carton	35757,40	9714,53	1,11	1,48	75,69	50616,14	9928,53	1,36	1,83	107,14	
Cellulose insulation	12403,46	2356,66	0,27	0,36	18,36	17557,63	2408,57	0,33	0,44	25,99	
Glass wool	1159,29	1449,12	0,16	0,22	11,29	1641,03	1481,04	0,20	0,27	15,98	
Acoustic board	26824,80	44931,54	5,11	6,86	350,06	37971,66	45921,35	6,31	8,47	495,53	
Steel studs	33609,60	81570,50	9,28	12,46	635,52	47575,83	83367,45	11,45	15,37	899,60	
Gypsum boards with carton	77054,96	20934,20	2,38	3,20	163,10	109074,61	21395,36	2,94	3,95	230,87	
Outer surface											
Acoustic board	1767,15	2959,98	0,34	0,45	23,06	2501,48	3025,18	0,42	0,56	32,64	
Windows and doors											
Windows	46744,00	51885,84	5,91	7,93	404,24	46744,00	51885,84	5,91	7,93	404,24	
Doors	25704,00	5963,33	0,68	0,91	46,46	25704,00	5963,33	0,68	0,91	46,46	
Glass wool	1022,24	1277,79	0,15	0,20	9,96	1022,24	1277,79	0,15	0,20	9,96	
Gypsum board	9049,59	2458,58	0,28	0,38	19,15	9049,59	2458,58	0,28	0,38	19,15	
Wood head /casing (pine/spruce)	258,77	14,23	0,00	0,00	0,11	258,77	14,23	0,00	0,00	0,11	
Shale	295000,00	63425,00	7,22	9,69	494,15	417585,19	64822,21	8,91	11,95	699,48	
Brick	95640,00	20562,60	2,34	3,14	160,20	135382,53	21015,58	2,89	3,88	226,78	
Steel studs	2199,13	5337,29	0,61	0,82	41,58	3112,97	5454,87	0,75	1,01	58,86	
Gypsum board	9679,76	2629,78	0,30	0,40	20,49	13702,11	2687,72	0,37	0,50	29,00	
A4 Transport		36169,67	4,12	5,53	281,80		36966,46	5,08	6,82	398,90	
Outer roof											
A1-A3											
Roof construction											
Reinforcement	2350,53	1362,02	0,16	0,21	10,61	2402,31	1392,03	0,14	0,19	10,85	

Reinforcement	2350,53	1362,02	0,16	0,21	10,61	2402,31	1392,03	0,14	0,19	10,85
Plywood	482,06	98,46	0,01	0,02	0,77	492,68	100,63	0,01	0,01	0,78
Gypsum boards (fire)	2444,90	924,17	0,11	0,14	7,20	2498,76	944,53	0,09	0,13	7,36
Glass wool	20,16	25,20	0,00	0,00	0,20	20,60	25,76	0,00	0,00	0,20
Prefabricated conrete slab	23312,00	4289,41	0,49	0,66	33,42	23825,55	4383,90	0,43	0,58	34,16
Wood boards (tounged and grooved) and joist (pine/spruce)	18356,59	1009,61	0,11	0,15	7,87	18760,97	1031,85	0,10	0,14	8,04
Wood surface boards (ceder)	52,62	90,82	0,01	0,01	0,71	53,78	92,82	0,01	0,01	0,72
Concrete (C35/45 vct 0,50 8/11)	102055,80	13267,25	1,51	2,03	103,37	104304,03	13559,52	1,34	1,81	105,64
Gypsum boards with carton	7670,16	2083,98	0,24	0,32	16,24	7839,13	2129,89	0,21	0,28	16,59
Roof eaves										
Wood surface boards (ceder)	74,00	127,72	0,01	0,02	1,00	75,63	130,54	0,01	0,02	1,02
Plywood	507,90	103,74	0,01	0,02	0,81	519,09	106,02	0,01	0,01	0,83
Wood studs	2515,75	138,37	0,02	0,02	1,08	2571,17	141,41	0,01	0,02	1,10
Cellulose insulation	1469,66	279,24	0,03	0,04	2,18	1502,04	285,39	0,03	0,04	2,22
Roof trusses										
Cross laminated timber	7320,00	1024,80	0,12	0,16	7,98	7481,26	1047,38	0,10	0,14	8,16
Aluzinc steel sheet	6145,00	14913,92	1,70	2,28	116,19	6280,37	15242,46	1,51	2,03	118,75
Terrasses										
EPS insulation	85,70	334,23	0,04	0,05	2,60	85,70	334,23	0,04	0,05	2,60
Reinforcement	4933,24	2858,58	0,33	0,44	22,27	4933,24	2858,58	0,33	0,44	22,27
Wood studs	5939,02	326,65	0,04	0,05	2,54	5939,02	326,65	0,04	0,05	2,54
Gypsum boards without carton	445,12	120,94	0,01	0,02	0,94	445,12	120,94	0,01	0,02	0,94
glass wool	74,02	92,53	0,01	0,01	0,72	74,02	92,53	0,01	0,01	0,72
Concrete (C28/35 vct 0,55 4/8)/(C35/45 vct 0,5	187167,63	24331,79	2,77	3,72	189,57	187167,63	24331,79	2,77	3,72	189,57
Prefabricated concrete slabs	40548,00	7460,83	0,85	1,14	58,13	40548,00	7460,83	0,85	1,14	58,13
A4 Transport		9520,64	1,08	1,45	74,18		9730,38	0,97	1,30	75,81
Foundation										
A1-A3										
Foundation structure										
Reinforcement	27018,94	15656,20	1,78	2,39	121,98	27614,15	16001,10	1,59	2,13	124,66
Clay aggregated blocks	130,56	51,31	0,01	0,01	0,40	133,44	52,44	0,01	0,01	0,41
Form (plywood)	2506,06	511,85	0,06	0,08	3,99	2561,27	523,12	0,05	0,07	4,08
EPS insulation	125,28	488,61	0,06	0,07	3,81	128,04	499,37	0,05	0,07	3,89
Concrete (C35/45 vct 0,40 8/11 S4)	592089,32	105983,99	12,06	16,19	825,72	605132,67	108318,75	10,74	14,42	843,91
Slab										
EPS insulation	9769,91	38102,65	4,34	5,82	296,86	9985,13	38942,03	3,86	5,18	303,40
Reinforcement	10341,13	5992,20	0,68	0,92	46,69	10568,94	6124,20	0,61	0,82	47,71
Concrete (C35/45 vct 0,40 8/11 S4)	769202,00	137687,16	15,67	21,03	1072,72	786147,04	140720,32	13,96	18,73	1096,35
A4 Transport		10240,56	1,17	1,56	79,78		10466,15	1,04	1,39	81,54
A5 Construction	8786 MJ	237222,00	27,00	36,2392	1848,20	8786 MJ	237222,00	27,00	36,2392	1848,20

assumed to be same for both cases

Maintenance and replacement (module B2, B4-B5)

B2	Intervention	kg/ apartment	Interval (years)	Reference — kg CO2 -eq/apartment for respective reference study period						comments
				30	50	60	80	100	160	
Bricks	New external mortar (25 mm)	208,00	25	27,75	27,75	55,50	83,25	83,25	166,51	Impact for A1-A5 assumed to be same as concrete (nonreinforced)
Windows (wood/ aluminium frame)	repainting	0,35	10	3,07	6,15	7,68	10,76	13,83	23,05	Impact for A1-A5 taken from ecoinvent. A white alkylid paint is used and assumed to be same for all: "alkyd paint production"
Doors	repainting	0,38	10	3,34	6,67	8,34	11,68	15,01	25,02	
Aluzinc steel sheet	repainting	1,58	12	15,04	30,08	30,08	45,12	60,16	97,76	
Balcony/ balcony access slab	5% replaced	148,30	25/23	24,66	49,32	49,32	73,98	98,64	123,29	
B2	**Intervention**	**kg/ apartment**	**Interval (years)**	**Flexible — kg CO2 -eq /apartment for respective reference study period**						
				30	**50**	**60**	**80**	**100**	**160**	
Bricks	New external mortar (25 mm)	313,00	25	41,76	41,76	83,52	125,28	125,28	250,56	Impact for A1-A5 assumed to be same as concrete
Windows (wood/ aluminium frame)	repainting	0,35	10	3,07	6,15	7,68	10,76	13,83	23,05	Impact for A1-A5 taken from ecoinvent. A white alkylid paint is used and assumed to be same for all: "alkyd paint production"
Doors	repainting	0,38	10	3,34	6,67	8,34	11,68	15,01	25,02	
Aluzinc steel sheet	repainting	1,62	12	15,41	30,76	30,76	46,14	61,53	99,98	
Balcony/ balcony access slab	5% replaced	156,54	25/23	24,66	49,32	49,32	73,98	98,64	123,29	

B4	Interval (years)	tot kg	Reference case — tot kg CO2 -eq for respective reference study period						comments
			30	50	60	80	100	160	*Transport for B2 and B4 is estimated by multiplying the share of the weight of each building element in relation to the weight of the building part to the transport of each building part*
Bricks	80	95640,00	0,00	0,00	0,00	0,00	26529,45	26529,45	
Shale	75	295000,00	0,00	0,00	0,00	81829,66	163659,33	163659,33	
Windows (wood/ aluminium frame)	40	57074,60	0,00	59753,55	59753,55	119507,10	119507,10	179260,64	
Doors	40	25704,00	0,00	8600,27	8600,27	17200,54	17200,54	25800,80	
Aluzinc steel sheet	40	6145,00	0,00	15072,69	15072,69	15072,69	30145,38	45218,08	
Balcony/ balcony access slab	60	380700,00	0,00	0,00	0,00	60352,22	60352,22	120704,44	
B4	**Interval (years)**	**tot kg**	**Flexible case — tot kg CO2 -eq for respective reference study period**						
			30	**50**	**60**	**80**	**100**	**160**	
Bricks	80	135382,53	0,00	0,00	0,00	0,00	37553,58	37553,58	
Shale	75	417585,19	0,00	0,00	0,00	115833,41	231666,82	231666,82	
Windows (wood/ aluminium frame)	40	57074,60	0,00	59753,55	59753,55	119507,10	119507,10	179260,64	
Doors	40	25704,00	0,00	8600,27	8600,27	17200,54	17200,54	25800,80	
Aluzinc steel sheet	40	6280,37	0,00	15404,73	15404,73	15404,73	30809,47	46214,20	
Balcony/ balcony access slab	60	401850,00	0,00	0,00	0,00	63300,95	63300,95	126601,91	

Refurbishment (module B5)

B5	tot kg	Flexible case 1				Flexible case 2			
		kg CO2 eq	kg CO2 eq/BTA	kg CO2 eq/BOA	kg CO2 eq/ apartmen t	kg CO2 eq	kg CO2 eq/BTA	kg CO2 eq/BOA	kg CO2 eq/ apartment
Load bearing structure									
Floors		0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Walls	693417,93	0,00	0,00	0,00	0,00	189578,54	18,80	25,24	1477,01
Room forming elements									
Inner walls	243551,57	154741,57	15,35	20,60	1205,59	154741,57	15,35	20,60	1205,59
Facade									
Curtain wall	265781,10	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Outer surface	572284,28	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Windows and doors	82778,60	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Roof									
Roof construction	167679,08	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Outer surface	6280,37	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
terrasse		0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Foundation		0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

B5	tot kg	Flexible case 3			
		kg CO2 eq	kg CO2 eq/BTA	kg CO2 eq/BOA	kg CO2 eq/ apartment
Load bearing structure					
Floors		0,00	0,00	0,00	0,00
Walls	693417,93	189578,54	18,80	25,24	1477,01
Room forming elements					
Inner walls	243551,57	154741,57	15,35	20,60	1205,59
Facade					
Curtain wall	265781,10	260303,29	25,82	34,66	2028,03
Outer surface	572284,28	149633,55	14,84	19,92	1165,80
Windows and doors	82778,60	66202,34	6,57	8,81	515,78
Roof					
Roof construction	167679,08	28613,30	2,84	3,81	222,93
Outer surface	6280,37	15388,72	1,53	2,05	119,89
terrasse		0,00	0,00	0,00	0,00
Foundation		0,00	0,00	0,00	0,00

End of life phase (module C1-C4)

<table>
<tr><th rowspan="3">C1-C4</th><th rowspan="3">end of life scenario</th><th colspan="5">Ecoinvent input data to Open LCA</th><th>Impact</th><th rowspan="3">comment</th></tr>
<tr><th>C1</th><th colspan="2">C2</th><th>C3</th><th>C4</th><th rowspan="2">kgO2 eq/ kg material</th></tr>
<tr><th></th><th>km</th><th>transport type</th><th></th><th></th></tr>
<tr><td>Concrete</td><td>recycling</td><td>inluded in C3</td><td>15</td><td>transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | cut-off, S</td><td>treatment of waste concrete, not reinforced, sorting plant | waste concrete, not reinforced | cut-off, U</td><td>.</td><td>0,00942</td><td></td></tr>
<tr><td>Reinforced conrete</td><td>recycling</td><td>inluded in C3</td><td>15</td><td>transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | cut-off, S</td><td>treatment of waste reinforced concrete, sorting plant | waste reinforced concrete | cut-off, U</td><td>.</td><td>0,01096</td><td></td></tr>
<tr><td>Reinforement</td><td>recycling</td><td>inluded in C3</td><td>15</td><td>transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | cut-off, S</td><td>treatment of waste reinforcement steel, sorting plant | waste reinforcement steel | cut-off, U</td><td>.</td><td>0,06117</td><td></td></tr>
<tr><td>Steel</td><td>recycling</td><td>inluded in C3</td><td>15</td><td>transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | cut-off, S</td><td>treatment of waste bulk iron, excluding reinforcement, sorting plant | waste bulk iron, excluding reinforcement | cut-off, U</td><td>.</td><td>0,00284</td><td></td></tr>
<tr><td>Window frames</td><td>recycling</td><td>inluded in C3</td><td>15</td><td>transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | cut-off, S</td><td>treatment of waste glass pane in burnable frame, sorting plant | waste glass pane in burnable frame | cut-off, U</td><td>.</td><td>0,02122</td><td rowspan="2">mass of glass and frame is estimated from Elitfönster (2007)</td></tr>
<tr><td>Widow panes</td><td>deposit</td><td>inluded in C3</td><td>15</td><td>transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | cut-off, S</td><td>treatment of waste glass pane in burnable frame, sorting plant | waste glass pane in burnable frame | cut-off, U</td><td>treatment of waste glass, inert material landfill | waste glass | cut-off, U</td><td>0,02658</td></tr>
<tr><td>Aluzink steel sheet</td><td>recycling</td><td>inluded in C3</td><td>15</td><td>transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | cut-off, S</td><td>treatment of waste bulk iron, excluding reinforcement, sorting plant | waste bulk iron, excluding reinforcement | cut-off, U</td><td>.</td><td>0,00284</td><td></td></tr>
<tr><td>glass wool insulation</td><td>deposit</td><td>inluded in C3</td><td>15</td><td>transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | cut-off, S</td><td>.</td><td>treatment of waste mineral wool, inert material landfill | waste mineral wool, for final disposal | cut-off, U</td><td>0,00788</td><td>mineral wool chosen because lack of data</td></tr>
<tr><td>gypsum boards</td><td>depost</td><td>inluded in C3</td><td>15</td><td>transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | cut-off, S</td><td>.</td><td>treatment of waste gypsum, inert material landfill | waste gypsum | cut-off, U</td><td>0,00788</td><td></td></tr>
<tr><td>cellulose insulation</td><td>incineration</td><td>inluded in C3</td><td>15</td><td>transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | cut-off, S</td><td>.</td><td>treatment of waste wood, untreated, municipal incineration with fly ash extraction | waste wood, untreated | cut-off, U</td><td>0,01841</td><td>wood chosen because lack of data</td></tr>
<tr><td>EPS insulation</td><td>incineration</td><td>inluded in C3</td><td>15</td><td>transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | cut-off, S</td><td>.</td><td>treatment of waste polystyrene, municipal incineration with fly ash extraction | waste polystyrene | cut-off, U</td><td>3,20021</td><td></td></tr>
<tr><td>wood</td><td>incineration</td><td>inluded in C3</td><td>15</td><td>transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | cut-off, S</td><td>treatment of waste wood, post-consumer, sorting and shredding | wood chips, from post-consumer wood, measured as dry mass | cut-off, U</td><td>treatment of waste wood, untreated, municipal incineration with fly ash extraction | waste wood, untreated | cut-off, U</td><td>0,03696</td><td></td></tr>
<tr><td>Bricks /shale</td><td>recycling</td><td>inluded in C3</td><td>15</td><td>transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | cut-off, S</td><td>waste brick | treatment of waste brick, sorting plant</td><td>.</td><td>0,00879</td><td></td></tr>
<tr><td>Doors</td><td>incineration</td><td>inluded in C3</td><td>15</td><td>transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | cut-off, S</td><td>.</td><td>treatment of used door, outer, wood-aluminium, collection for final disposal | used door, outer, wood-aluminium | cut-off, U</td><td>0,04899</td><td>mass of one door is estimated to be 46 kg and the area 2 m^2</td></tr>
<tr><td>Clay aggregated block</td><td>recycling</td><td>inluded in C3</td><td>15</td><td>transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | cut-off, S</td><td>treatment of waste concrete, not reinforced, sorting plant | waste concrete, not reinforced | cut-off, U</td><td></td><td>0,00942</td><td>dataset assumed to be same as conrete</td></tr>
<tr><td>mortar</td><td>deposit</td><td>inluded in C3</td><td>15</td><td>transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | cut-off, S</td><td>.</td><td>treatment of waste cement in concrete and mortar, collection for final disposal | waste cement in concrete and mortar | cut-off, U</td><td>0,01509</td><td></td></tr>
<tr><td>paint</td><td>deposit</td><td>inluded in C3</td><td>15</td><td>transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | cut-off, S</td><td>.</td><td>treatment of waste emulsion paint, inert material landfill | waste emulsion paint | cut-off, U</td><td>0,00536</td><td></td></tr>
</table>

Appendix II- Inventory: Prior calculations of module A1-A5 in BM

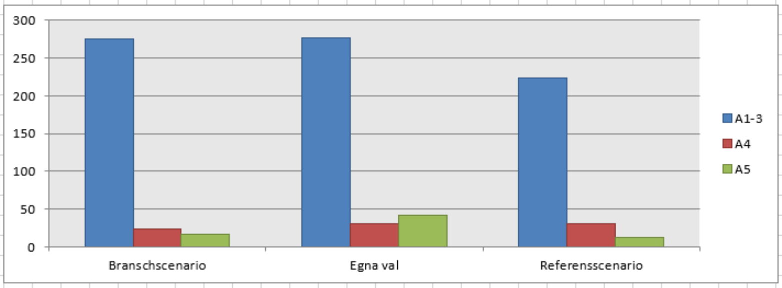
Klimatpåverkan för A1-5 Byggskedet, kg CO_2e per m²

Scenarion

Branschscenariot innehåller branschgemensamma transportavstånd, spill och miljödata för generiska produkter. Under "egna val" har mer specifika data valts. Referensscenariot sätts om det "egna valets" resultatet ska jämföras med ett valbart referensvärde eller kravvärde. Referensscenariot beskrivs av den som gör

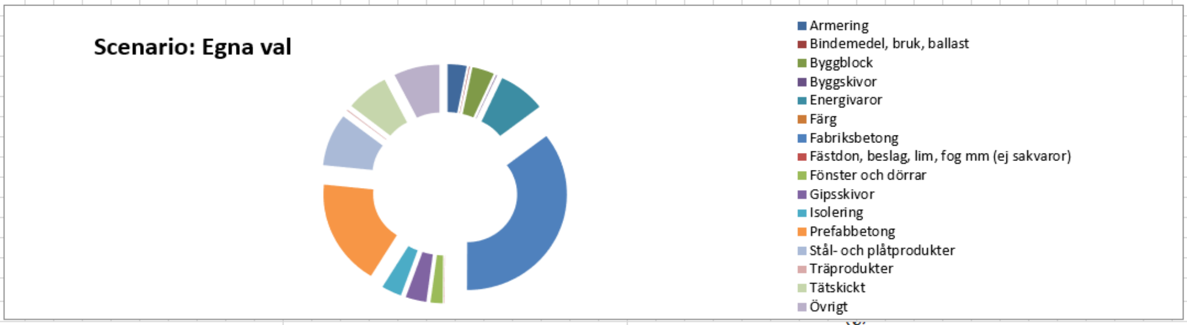
Nyckeltal

17%	Andel EPDer i förhållande till generiska resurser i scenariot "Egna val"
-11%	Klimatreduktion "Branscsc." i förhållande till "Egna val"
-18%	Klimatreduktion "Referensc." i förhållande till "Egna val"



Klimatpåverkan (GWP GHG), kg CO_2e per m² BTA	Branschscenario	Egna val	Referensscenario	Beskrivning av referensscenariot
A1-3 Produktskedet	275,67	276,77	223,28	
A4 Transport	23,49	31,21	30,6	
A5 Bygg- och installationsprocessen	16,29	42,27	12,38	
A5.1 Spill, emballage och avfallshantering	*16,28*	*15,27*		
A5.2 Byggarbetsplatsens fordon, maskiner och apparater	*0,01*	*27*		
A5.3 Energi till tillfälliga bodar, kontor, förråd och andra byg				
A5.4 Byggprocessens övriga energivaror				
A5.5 Övrig miljöpåverkan från byggprocessen				

Klimatpåverkan för alla byggresurser (inklusive spill), A1-5 Bygskedet, kg CO_2e per m²



Branschgemensamma resursgrupper	Armering	Bindemedel, bruk, ballast	Byggblock	Byggskivor	Energivaror	Färg	Fabriksbetong	Fästdon, beslag, lim, fog mm (e	Fönster och dörrar	Gipsskivor	Isolering	Prefabbetong	Stål- och plåtprodukter	Träprodukter	Tätskickt	Övrigt
Branschscenario	10,82	0,33	12,53	0,38	0,01		116,44	0,17	6,9	11,87	11,48	62,63	30,96	0,58	24,29	26,05
Egna val	10,82	0,33	12,53	0,38	27		124,29	0,17	6,9	11,86	11,48	62,61	30,95	0,58	24,29	26,05
Referensscenario																

Klimatpåverkan uppdelat per byggprojektdel (inklusive spill), A1-5 Bygskedet, kg CO_2e per m²

Branschgemensama byggprojektdelar	Sammansatta byggdelar	Mark	Husunderbyggnad	Stomme	Yttertak	Fasader	Stomkomplettering/rumsbildning	Invändiga ytskikt/rumskomplettering	Installationer	Gemensamma arbeten/tillfälliga fabriken
Branschscenario		1,36	34,31	161,21	9,34	39,75	20,86	22,56	26,05	
Egna val		1,4	35,82	167,18	9,65	39,75	20,85	22,56	26,05	
Referensscenario										

Appendix III- Calculation of maintenance quantities

The estimation of quantities subject to maintenance interventions are explained here. The quantity of mortar of the brick facade and paint for windows and doors is calculated per apartment to give a more accurate comparison between the reference and flexible case.

Mortar of the brick facade

The amount of mortar of the brick façade that is subject to maintenance is estimated based on a mortar usage of 65 kg/ m^2 brick facade (Finja, 2014). According to Kahangi et al. (2020) approximately the 25 outer mm are subject to maintenance. The bricks of the façade are assumed to be of the size 250x120x62 mm. Further the area of the façade of one apartment is 16.32 m^2 for the reference case and 23.10 m^2 for the flexible case, according to a 3D model and estimations from floor plan drawings.

This means that the estimated kg of mortar for each apartment and each maintenance is:

Reference case: $65x16.32x\left(\frac{25}{120}\right) = 221\ kg/apartment$

Flexible case: $65x23.10x\left(\frac{25}{120}\right) = 313\ kg/apartment$

Paint for the steel sheets

The area that needs repainting is estimated based on the kg of steel sheets, 6145 kg for the reference case and 6280 kg for the flexible case. According to Plannja (2020) the density of a steel sheet is 5.8 kg/m^2. This means that the approximate area of the steel sheets is 6145/5.8 for the refence case and 6280/5.8 for the flexible case. According to Kramp (n.d.) the paint use is 6 m^2/litre and according to Hagmans (2017) the density is 1150 kg/m^3.

This means that the estimated kg of paint used for the whole building and each maintenance is:

Reference case: $\frac{6145}{5.8}/6\ \ x\ 1.150 = 203\ kg$

Flexible case: $\frac{6280}{5.8}/6\ x\ 1.150 = 208\ kg$

Paint for the windows

The amount of paint that is needed for the maintenance of the windows is estimated based on the estimation that the windows are of the size 1230x1480 mm. According to Elitfönster (2019) the width of the window frame is 84 mm, which gives an area of 0.084x(1.23x2+1.48x2)=0.46 m^2 which compared to an approximation of frame area made by Teknos (n.d.) of 0.5 m^2 seems reasonable. The same paint use and density is assumed as for the steel sheet (of 6 m^2/litre and 1150 kg/m^3). Each apartment (of both reference and flexible case) has three windows and one balcony door, the balcony door is estimated to need the same amount of paint as the windows.

This means that the estimated kg of paint used for each apartment and each maintenance is:

$$\frac{0.084\text{x}(1.23\text{x}2+1.48\text{x}2)}{6}\text{x}\ 1.15\text{x}\ 4 = 0.35\ kg\ /apartment$$

Paint for the front doors

The amount of paint that is needed for the maintenance of the doors is estimated based on the estimation that the doors are 2 m^2. The same paint use and density is assumed as for the steel sheet (of 6 m^2/liter and 1150 kg/m^3). Each apartment (of both reference and flexible case) has one front door.

This means that the estimated kg of paint used for each apartment and each maintenance is:

$$\frac{2}{6} \text{x } 1.15 = 0.38\ kg\ /apartment$$

Concrete of the balcony and balcony access

Based on a report by Liljenström et al. (2015), approximately 5 % of the balcony can be assumed to be replaced during maintenance. The total area of the balconies and balcony access for the whole building is estimated based on floor plan drawings to 1080 m^2 for the reference case and 1140 m^2 for the flexible case. The thickness of the balcony is assumed to be 150 mm. The density of the concrete is further assumed to be 2350 kg/m^3 (Betongindustri n.d.).

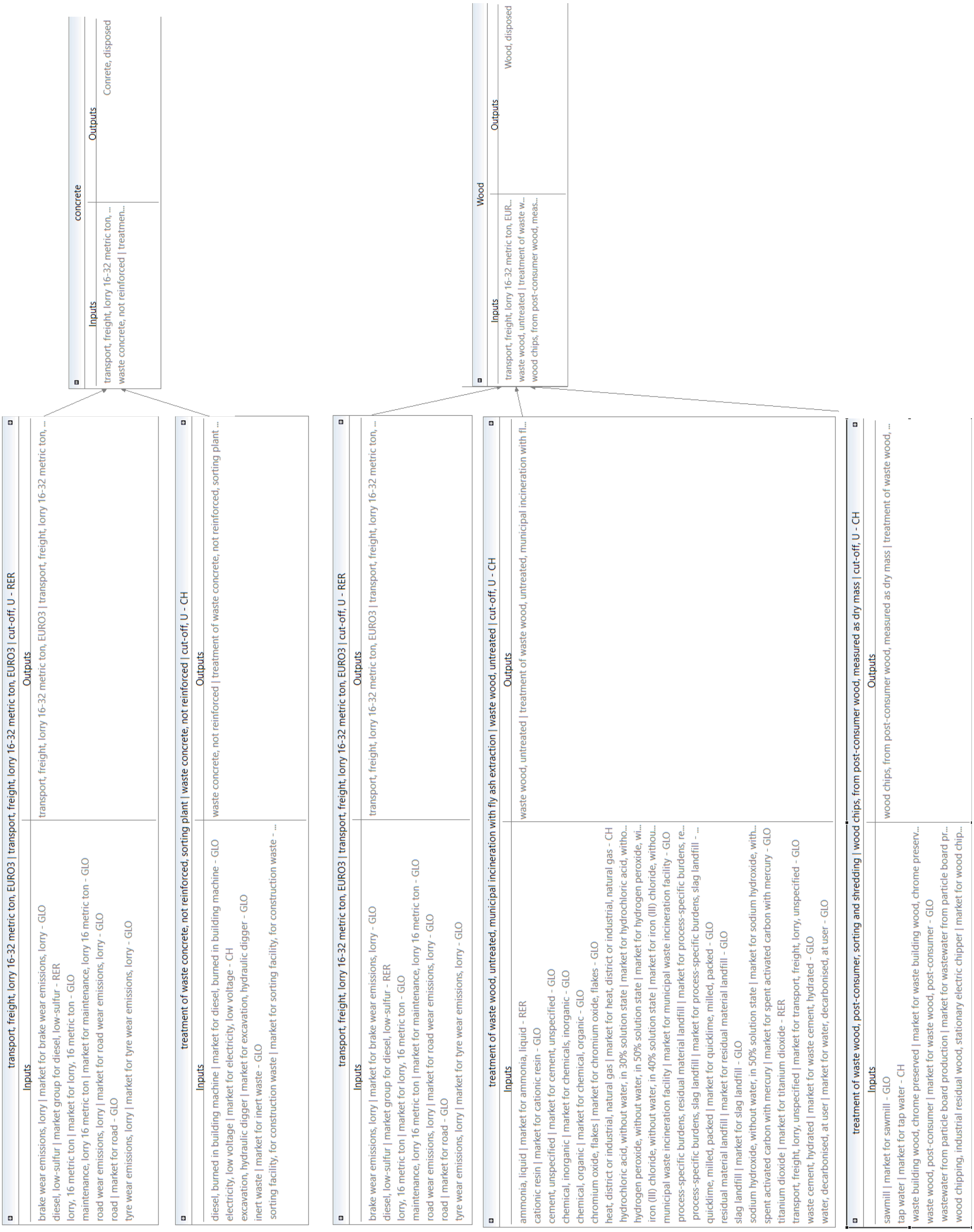
This means that the estimated kg of concrete of the whole building subject to one maintenance is:

Reference case: $0.05x(1080x0.15)x2350 = 19035.0\ kg$

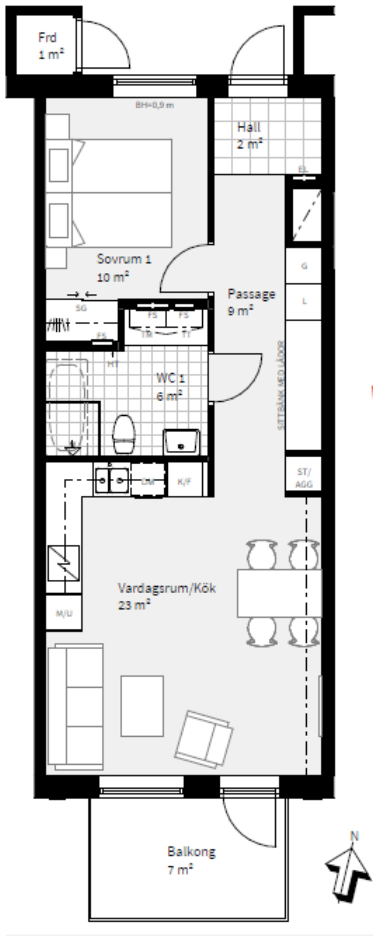
Flexible case: $0.05x(1140x0.15)x2350 = 20092.5\ kg$

Appendix IV- Modelling of end of life in OpenLCA

Example of a modelled product systems- Concrete and wood



Appendix V- Site plan and floor plan of Varvsporten



Drawings from PEAB (n.d.)

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