# The Impact of Life Expectancy in LCA of Concrete and Massive Wood Structures

## A Case Study of Strandparken in Sundbyberg

Master of Science Thesis in the Master's Programme Structural Engineering and Building Technology

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Department of Civil and Environmental Engineering
Division of Building Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2014
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Cover:
Erection of residential buildings Strandparken. To the left with prefab concrete by Wåhlin Fastigheter and to the right in massive wood by Folkhem. © Jonas Lundgren

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ABSTRACT

Recently there has been an increase of energy and environmental certifications in the Swedish building sector which has led to the development of more energy-efficient building operation systems. Contradictory to this the *greenhouse gas emissions* for construction, maintenance, disposal and the other associative building sector stages have increased. The methodology of *Life Cycle Assessment* with its *cradle-to-grave* approach can be used to holistically evaluate the environmental load impacts of the entire building process. The building's frame structure represents the largest part of material mass and is therefore crucial in the climate impact of the construction sector. Within the last ten years there have been several LCA comparisons between concrete and massive wood frames. These analyses more or less lack a life span perspective of each structural material. Life spans of buildings vary considerably due to climate conditions, lack of construction quality and maintenance continuity. In most cases the building life span is not depending on the structure, and additionally no consensus in variation of life span between the frame materials can be found.

An LCA of two newly-raised multi-residential houses in the neighbourhood of Strandparken in Sundbyberg is performed comparing a *CLT* (Cross Laminated Timber) structure with a semi-prefabricated concrete system, using same construction requirements for fire, acoustics and insulation. The assessment results with limited system boundaries shows including variation of life expectancies that the carbon emission impact by wood and concrete is approximately the same. By extending the system boundaries to include *reforestation* the most outstanding reason for building with long-lasting wooden structures is the great potential of biogenic storage of carbon dioxide. In a complementary sensitivity analysis it is shown that through balanced harvesting and replanting methods it is possible to make the life cycle of wooden buildings close to climate neutral and act as a *carbon sink* for global warming. It is also concluded that the end usage phase is crucial for both materials where combusted wood could substitute fossil fuels or continue as carbon storage. Concrete on the other hand has a potential through *carbonatation* of rebinding up to half of its released fossil carbon dioxide at production, but wood as construction material is still a preferable choice for a future decreased climate impact by the building sector.

Keywords: energy-efficient buildings, greenhouse gas emissions, life span, LCA, cradle-to-grave, life expectancy, CLT, concrete, reforestation, carbon sink, carbonatation

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*Examensarbete för Master of Science på masterprogram Structural Engineering and Building Technology*

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SAMMANFATTNING

De senaste årens uppsving av energi- och miljöcertifieringssystem inom den svenska byggsektorn har lett till mer energieffektiva byggnader med reducerat värmebehov i användningsfasen. I motsats till detta har utsläppen av växthusgaser för byggnadssektorns övriga faser ökat. Den inbundna energin i materialen genom utvinning, produktion, konstruktion, underhåll, rivning, nedmontering, återvinning och deponi blir mer betydande om energiförbrukningen i användningsfasen minskar. *LCA*, livscykelanalys, med sin helhetssyn ”från vaggan till graven" studerar i detalj hela livscykeln för att kunna utvärdera miljöpåverkan av hela byggprocessen.

Byggnadens stomkonstruktion representerar den största delen av byggnadens material och är därför avgörande för att minska klimatpåverkan av byggsektorn. De senaste tio åren har många livscykelanalyser jämfört betongstommar mot stommar av massivträ. Dessa jämförelser saknar mer eller mindre ett livslängdsperspektiv hos respektive stommaterial. Byggnaders livslängd varierar kraftigt på grund av klimatförehållande, bristande kvalité vid byggnation och kontinuitet i underhåll. Alltså är i de flesta fall byggnaders livslängd inte beroende av stommen, och dessutom saknas konsensus i skillnad i livslängd mellan stommaterialen.

En LCA av två nybyggda flerbostadshus på Hamngatan i Sundbyberg har utförts jämförande en prefabricerad stomme av *KL-trä* (Brf Strandparken) med en halvt prefabricerad stomme i *betong* (Kv Tvättstugan), där samma konstruktionskrav för brand, akustik och isolering har antagits. Genom att variera den förväntade livslängden för strukturerna och begränsa systemgränserna visar det sig att klimatpåverkan av växthusgaser av betong och trä är ungefär lika stora. Genom att utöka systemgränserna att även innefatta återplantering är den stora anledningen till att bygga med långlivade trästommar fördelen av biogen lagring av koldioxid. I en kompletterande noggrannhetsanalys visas att genom balanserat skogsbruk är det möjligt att göra livscykeln av träbyggnader närapå klimatneutral och genom lagringen fungera som en *kolsänka* för global uppvärmning. Det visas också att slutanvändningsfasen är betydande för båda materialen där trä antingen kan förbrännas med energiutvinning som kan ses som ersättning av fossila bränslen eller fortsätta som kollagring. Betong har istället potential att genom *karbonatisering* återbinda upp till hälften av den utsläppta fossila koldioxiden vid produktion, men trä som konstruktionsmaterial är fortfarande att föredra för en framtida minskande klimatpåverkan av byggsektorn.

Nyckelord: energieffektiva byggnader, livslängd, LCA, KL-trä, Brf Strandparken, betong, kv Tvättstugan, återplantering, kolsänka, karbonatisering

# Contents

# Preface

This master's thesis was written as a final work of the master's programme *Structural Engineering and Building Technology* at Chalmers University of Technology. The thesis has been carried out with Professor Holger Wallbaum as examiner and supervisor at the Division of Building Technology under the Department of Civil and Environmental Engineering.

Information on the case study of the newly raised multi-residential buildings of Strandparken in Sundbyberg has been obtained through e-mail and phone calls, construction documents and preliminary studies, and finally a study visit on site. For the wooden structure housing the work has been performed in collaboration with the developers *Folkhem*, the architects *Wingårdhs*, the engineers *Tyréns* and wooden structure prefabricators *Martinsons*. A thanks go out to *Anna Höglund* and *Hanna Samuelson* at Wingårdhs, *Anders Wernborg* and *Stefan Karlsson* at Folkhem, and *Håkan Risberg* and *Cecilia Pettersson* at Martinsons for distributing material and knowledge about the project. For knowledge about the concrete housing by *Wåhlins Fastigheter* information of the prefab concrete structural system was collected through the developer *Boetten Bygg* and the prefabricator *Con-Form Stockholm* and their homepages. Thanks also go out to my opponent *Shea Hagy* and my colleague *Peter Selberg* who I have been able to discuss topics and results with.

Jonas Lundgren has a background in the interdisciplinary bachelor program *Architecture and Engineering* at Chalmers University and is, parallel with the civil engineering master program, studying the master program *Design for Sustainable Development* at Chalmers Department of Architecture. With an underlying interest for sustainable architecture and involvement in Chalmers and Halo Team Sweden's participation in *Solar Decathlon China 2013*, the aim for this thesis is to get comprehensive and deeper knowledge regarding sustainable choices of the most common building materials. The result of the thesis is an initiation to a second thesis work taking place at the master program Design for Sustainable Development in the spring of 2014. The architectural thesis is set out to study basic living needs through developing emergency housing in refugee camps. By replacing existing plastic or fabric tents with a light, flat packaged and fully recyclable wooden paperboard, it can result in improved living conditions with an environmentally low impact.

Göteborg, December 2013

Jonas Lundgren

# Notations

**Translations of names of institutes, certifications or municipalities**

| | |
|---|---|
| ASHRAE | American Society of Heating, Refrigerating and Air Cond. Engineers |
| BBR | Boverket's Building Regulations |
| BBSR | German Federal Institute for Research on Building and Urban Affairs |
| Boverket | Swedish national board of housing, building and planning |
| BREEAM | Building Research Establishment Environmental Assessment Method |
| CEN | Comité Européen de Norm., European Committee for Standardization |
| GaBi | Ganzheitliche Bilanz, Life cycle assessment modelling software |
| ELCD | European reference Life-Cycle Database |
| EU | European Union |
| IPCC | UN's Intergovernmental Panel on Climate Change |
| ISO | International Organization of Standardization |
| IVL | Swedish Environmental Research Institute |
| LEED | Leadership in energy and Environmental Design |
| SCB | Statistics Sweden, national administrative agency |
| SEMCo | Swedish Environmental Management Council |
| SGBC | Swedish Green Building Council |
| SIA | Swiss Society of Engineers and Architects |
| SP | Technical Research Institute of Sweden |
| Sundbyberg | Municipality and suburb located North West of Stockholm, Sweden |
| UN | United Nations |

**Abbreviations**

| | |
|---|---|
| CED | Cumulative Energy Demand |
| CLT | Cross Laminated Timber |
| $CO_{2,eq.}$ | Amount of carbon dioxide equivalent to GHG used to calculate GWP [1] |
| CPD | Construction Productive Directive |
| EPD | Environmental Product Declaration |
| GHG | Green House Gases |
| GWP | Global Warming Potential |
| ILCD | International Reference Life Cycle Data system handbook |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| RCA | Recycled Concrete Aggregate |

[1] UN IPCC, *Fourth Assessment Report, Working Group I: Chapter 2*, 2007.

# 1 Introduction

Sweden has a strong vernacular tradition of building in wood. Solid timber, log cabins, wooden façade panels and light frame structures are still common features in single-family housing. The cultural and economic influence of more globalized materials as concrete and steel made its conquering during the modernistic reformation during the beginning of the 20th century. The knowledge diversity of building with masonry, wood and stone was rationalized and notions as façade embellishment and decorative mouldings are today lost knowledge. Contributing to the regress of building with wood was the high number of city fires that 1874 lead to a prohibition of building more than two-storey buildings in wood[2]. During the 1960's the government invested in *Miljonprogrammet* with a progressive fabrication model which resulted a million multi-residential homes, most of them built with a structure casted in reinforced concrete. A reformation which left its imprint and today has become prevalent. In 1994 a CPD (Construction Productive Directive) of EU was introduced to Sweden and the old prohibition of wooden multi-storeys was repealed.

The last decade projects with multi-storey timber building have tried to claim market but often developer's short-term economic perspective and lack of knowledge in building with wood slows down the increase in market share. Today around 10 % of all new multi-residential housing in Sweden is built with a wooden frame[3]. As some of the wooden construction companies are paving the way with taller and taller wooden multi-residential buildings the developers have their eyes opened to wood as an alternative. The proportion of newly-built multi-residential buildings in wood is assumed to increase, while the current height boost will stagnate at around 20 storeys because of structural limitations as e.g. increasing slab thickness.

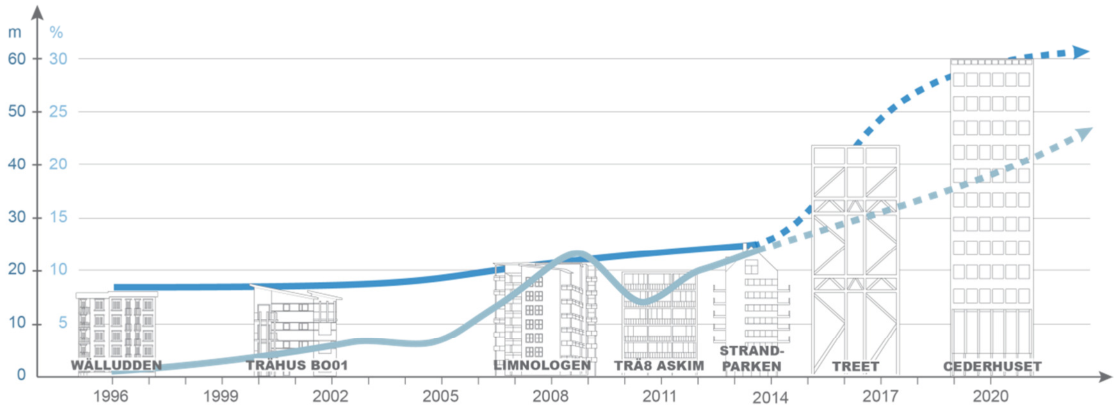



*Figure 1. Height (blue) of pioneer projects and percentage (light blue) of newly built multi-residential buildings with wooden frames in Scandinavia with future prediction of increase.*

[2] Bergström, *Svensk Byggnadsstadga*, 1874.
[3] SCB, "Träandel - Flerfamiljsbostäder.", www.tmf.se/statistik/, Dec. 2013.

The energy and environmental certifications for building has led to more energy-efficient air handling systems, air-tighter and better insulated building envelopes and healthier choices of materials. A lot is though left to be done for energy usage and greenhouse gas emissions in the primary production and disposal phase. An evidence of that you find in the latest national status report for the sectors emissions of greenhouse gases[4], shown adapted in Figure 2. From 1993 to 2007 the emissions from heating of buildings in Sweden dropped from 15 to 7 Mtonnes $CO_{2,eq}$. For the rest of the building sector stages, that is mainly material extraction, production and end use, for the same period the emissions increased from 9 to 11 Mtonnes $CO_{2,eq.}$

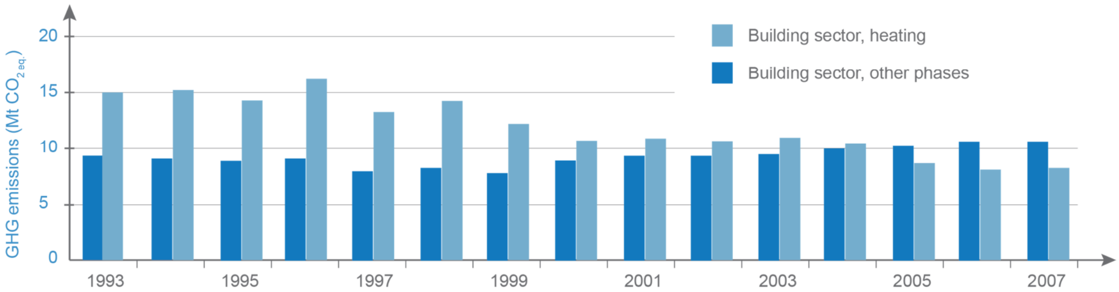



*Figure 2. Emissions of heating versus other phases of the Swedish building sector.*

The energy consumption of material production and assembling is an important factor neglected by the established certifying systems. Supporting the holistic approach of looking at all stages of a product's life is the technique of LCA, *Life Cycle Assessment*, which with its holistic approach "*cradle-to-grave*" in detail studies the stages of raw materials extraction, manufacture and production, distribution, construction, use, maintenance, disassembly or demolition and possible end use alternatives as disposal, landfill, incineration (energy recovering combustion), storage, reusing or recycling. The later also referred to as *cradle-to-cradle*.

From an economic standpoint a longer life span for buildings than 50 years is often not foreseeable. From the ecological point of view however the life span is more essential. Today there are about 4.5 million dwellings in Sweden whereof 2.5 million apartments in multi-residential housing. To reach EU climate goals for 2050 in halving the energy consumption and global emissions more than 50 000 apartments each year needs to be renovated to 50 % of its energy demand[5]. Add to that the importance of energy efficiency in new-erected buildings. If the production rate of today around 30 000 dwelling units a year[6] continues the existing building stock of 4.5 million dwellings must have a life span (including renovations) of well over 150 years to meet the demand. Whether or not the housing has that life span the fact is that, as the new production stagnates because of the absence of financial resources, the life span of buildings in the stock is increasing. The question of financial and environmental sustainability is if materials for structure, climate envelope and building services should be replaced often to meet updated energy efficiency demands or if a long-term investment with low maintenance cost is preferable.

[4] Boverket, *Lägesrapport*, p. 65, 2012.
[5] IVA, *Energieffektivisering Av Sveriges Flerbostadshus*, 2013.
[6] SCB, *Bostads- Och Byggnadsstatistisk Årsbok* , 2012.

## 1.1 Objective

The primary purpose of this thesis is to investigate how life expectancy assumptions of building materials affect results of Life Cycle Assessment, *LCA*. Emphasis is put on discussing the most common structural building systems, comparing the often seen as more sustainable material wood, with a structural alternative of concrete. Many studies like this have been done before and to get further into the topic the thesis circulates around some of these mentioned in chapter 1.2, comparing the results from a life expectancy perspective.

To obtain empirical results for comparison with existing research, a case study has been performed on the newly constructed multi-residential housing on Hamngatan in Sundbyberg. The seven houses in eight stories are overall designed by *Wingårdhs* is distributed by three different general contractors. Four of the multi-residential houses ("Brf Strandparken") contracted by *Folkhem* are built with cross laminated timber, CLT, elements prefabricated by *Martinsons* and are among the highest wooden residential buildings in Sweden. It has also drawn a lot of attention by its characteristic cedar chip façade. The house furthest North ("Kv. Tvättstugan") built by *Wåhlin Fastigheter* has the same shape as the others but is raised by *Boetten Bygg* using a half prefabricated concrete system by *Con-Form*. The LCA study will make a parallel comparison between these two frame structures with system boundaries, simplifications and assumptions to make them comparable. The two last buildings ("Brf Mälarporten") are erected by *JM* but will not be a part of the analysis.

*Figure 3. Brf Strandparken built with a CLT frame. In the background Kv Tvättstugan built in concrete.*

## 1.2 References

For references an LCA screening of the massive wood houses in an initial stage is already done by the engineer consultants *Tyréns*, where the massive wood frame was compared with an option of a concrete frame together with a similar concrete frame building project by Folkhem[7]. Another reference in focus of comparison is a new LCA study[8] made by the Technical Research Institute of Sweden *SP* looking at different wooden frame structure systems for multi-residential buildings and applied on the four-storey multi-residential housing built in 1996 named *Wälludden*. The results from SP tells that all the wooden structural systems demand less cumulative energy, especially from fossil energy sources, and less climate effect through reduced total emission of greenhouse gases. The results only from the production stage shows a 60% increase in the carbon footprint from the production stage a concrete building compared to a wooden building. These LCAs on wood and concrete structures and a number of others are compared with the case study results and interpreted in chapter 5 and 6.

While the energy demand for the operational stage is decreasing due to more energy-efficient systems the other stages in *cradle-to-grave* LCA is increasing in importance, e.g. the end-of-life treatment of building components and materials. For lumber and massive wood which in building frames are working as storage of carbon dioxide, which then is released in to the atmosphere when combusted. Researchers at Yale University in Connecticut and Norwegian University in Trondheim have in their study[9] from 2012 compiled, compared and developed the *dynamic LCA* model of calculating the *Global Warming Potential* (GWP) reduction of carbon storage in biomass. They compared variations of the forest rotation period 1-100 years and carbon storage 20-100 years and showed that a negative GWP was achieved when the storage time was more or equal to half of the forest rotation time. Accordingly there is potential of reducing climate change with an increase of carbon storage in the building stock resulting in a global delay of carbon emissions. A following study by researchers at École Polytechnique de Montréal[10] studied four end-of-life scenarios of wood using dynamic LCA and concluded that *refurbishment* or *landfill* could be alternatives to *incineration* (energy recovery by combustion). These papers are described further in chapter 6.1.2.

For concrete it is the opposite behaviour since the production phase is a big source of GHG emissions, predominantly during *calcination* of the cement clinker where carbon dioxide is released. Then during the life span the concrete holds possibilities to absorb carbon dioxide through *carbonatation*. A report[11] by the *Nordic Innovation Centre* from 2005 is presenting results of calculating carbonatation of the total concrete stock in the Nordic countries claims that 20 % of the emitted carbon dioxide from the calcination process could be absorbed during the operation phase and as much as 57 % after 30 years of air-available landfill storage. These results are not taking into account volume carbonatation and cement substitution reduction factors which is discussed in chapter 4.1.4.

[7] Bruzell, *Screening Avseende Klimatpåverkan Från Flerbostadshus*, 2012.
[8] Eriksson, et al., *Life Cycle Assessment of Different Building Systems*, 2012.
[9] Guest, et al., *Global Warming Potential of Carbon Dioxide Emissions from Biomass*, 2013.
[10] *Levasseur, et al., Biogenic Carbon and Temporary Storage Addressed with Dynamic LCA*, 2013.
[11] Kjellsen, et al., *The CO2 Balance of Concrete in a Life Cycle Perspective*, 2005.

## 1.3 Questions at issue

Based on these references the thesis is based on the following main questions:

- How is the ISO standardized methodology for LCA applied in the Swedish building sector?
- Which of the building materials concrete and wood has the lowest impact on global warming with a life span perspective for multi-residential buildings in Sweden?
- What alternatives for end use for structural wood respective concrete causes the less GHG emissions?
- What could be the solution to reverse the increasing GHG emission trend in the production phase in the building sector of Sweden?

## 1.4 Structure of the thesis

Applying the general and ISO standardized LCA methodology[12] (described in chapter 2.1) helps structuring up the process of the thesis. The perspective of life expectancy is brought into the assessment stage, where life spans of the structures and time horizon are alternated.

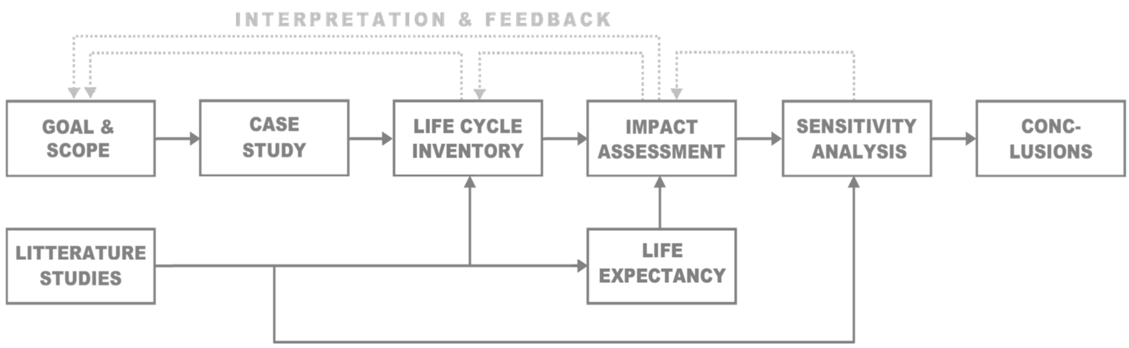



*Figure 4. Overall process for thesis.*

Chapter 1 to 3 are introduction chapters. While chapter 1 initiates the background, objective and methodology of the thesis, the following chapters will provide more details about subject and case study. Chapter 2 will introduce the LCA methodology and Swedish implementing together with a discussion of building's life expectancy. Chapter 3 is the introduction of the actual LCA defining the goal and scope and presenting the case study. The analysis part of the LCA is shown in chapter 4 to 6, where the inventory is displayed in chapter 4, and the results of the impact assessment is shown in chapter 5 which are discussed and interpreted in chapter 6 where two sensitivity analyses are done. Final conclusions are summarized in chapter 7.

[12] ISO, *ISO 14040:2006 Environmental Management LCA*, 2006.

# 2 Prestudy

Life Cycle Assessment, also known as LCA, stands out as an assessment methodology in material comparison and environmental impact investigation on the ground of its holistic perspective at looking at all stages in life of a product or service, from *cradle-to-grave*. This is including all the stages from raw material extraction, processing, manufacture, distribution, use, maintenance, and disposal or recycling. The methodology is implemented by performing an inventory of relevant energy, substance and material inputs, followed by evaluating and interpreting the potential environmental impacts. With identified and well-structured inputs and emissions the results help the LCA performer for overview to take more informed decision.

The history of life cycle and ecological balance analysis on material products and services stretches back as far as to the 1970's[13]. Among the forerunners in LCA you could find Swedish companies as Tetrapak and Volvo. After many decades of development, an internationally broad and well-established consensus led to the first ISO standard of LCA methodology 1997[14]. Though the building sector in Europe has been using LCA to a very limited extent, through the ISO standards[15], corresponding European CEN guidelines EN15978[16] and CEN/TC 350[17], together with the ILCD handbook[18] formulated by the JRC European Commission there is today a standardized base to stand on.

## 2.1 The LCA methodology

The ISO principles and framework established in 1997 were updated in 2006 and confirmed in 2010 and consists out of four distinct stages[19].

Essential of an LCA study is well defined questions, which is set up in a *goal and scope definition*. Otherwise the effluent results from the work may not be consistent with the intended application. Beside the *context*, *model specifications* and *project planning*, the choice of a *functional unit* is an important basis for quantifying and defining what precisely is being studied. *System boundaries*, *assumptions* and *limitations* is also set up together with *allocation methods* (to partition the environmental load of a process when products share the same process) and *impact categories* (e.g. resource use, human health or ecological consequences).

The goal and scope definition is followed by a *Life Cycle Inventory* (LCI). The inventory analysis means to build a systems flow model according to the defined requirements. Only the relevant flows are considered according to chosen functional unit and impact categories. The systems model is filled with collected input and output data of all activities, which is translated to the functional unit.

[13] Baumann and Tillman, *The hitchhiker's guide to LCA*, 2006.
[14] Ibid.
[15] ISO, *ISO 14040:2006 Environmental Management LCA*, 2006.
[16] CEN, *EN 15978:2011 Assessment of Environmental Performance of Buildings*, 2011.
[17] CEN/TC, *EN15643:2012 Sustainability of construction works*, 2012.
[18] JRC EC, *ILCD Handbook, 2010*.
[19] International Standard Organization, *ISO 14040:2006 Environmental Management LCA*, 2006.

The third part of the LCA study is the *Life Cycle Impact Assessment*. LCIA is aimed at evaluating the impact of the environmental loads quantified in the inventory analysis, using some mandatory elements. *Classification* is used to sort the inventory parameters in types of impact loads, e.g. sulphur oxide and hydrochloric acid go under acidification potential while carbon dioxide and methane go under global warming potential. *Characterisation,* meaning calculating relative class contribution of each parameter, then works to make the results comparative. Two final optional steps is *normalization*, i.e. comparing the results with the regional or global impact, and *weighting,* meaning to rate the different impact relative to each other and sum them up to a single number for total impact.

*Interpretation* is the final part of the study where the results from LCI and LCIA is identified, checked and evaluated. The outcome of the interpretation phase is a set of conclusions and recommendations for the study. This has to be communicated in a complete and accurate manner, to be able to achieve confidence in the final results.

## 2.2 Implementation in the Swedish building sector

In a more climate understanding society the Swedish building industry has started to take impact aspects of buildings seriously with emphasis on energy consumption. The influence of LCA in the environmental work of the Swedish building sector is still in an initial stage. For understanding first the more established environmental certification and labelling systems are described.

For energy performance declaration in buildings there is the Swedish standardized *SS 24300* based on the *BBR19-9* regulations by Boverket. In Sweden there are also several established certification systems. For energy usage there is the European *Greenbuilding*, the international *Passive House* standard from Germany and the implemented *FEBY12* by the Swedish Centre for Zero Energy Housing.

For a broader perspective there are also some environmental classification systems. In addition to energy consumption the Swedish certification system *Miljöbyggnad* emphasize material choices and indoor climate. The *Nordic Swan* is a well-known certification system applied mainly on multi-residential building and put weight in materials, estate management and energy. The international certification systems *LEED* (US) and *BREEAM* (UK) have a more holistic approach, also taking contamination, transports, land use, waste management, maintenance and innovative solutions into account. This year, 2013, a Swedish implementation *BREEAM-SE* has been introduced, adapted to Swedish standards and building codes by the Swedish Green Building Council *SGBC*[20]. In Figure 5 on next page you can see a comparison of levels of energy demands for different certifications and their internal grades. The gathered data is from the Swedish low energy building program *Lågan*[21] but here implemented for multi-residential buildings. The LEED certification system is excluded because energy demands are calculated by the American ASHRAE system.

[20] SGBC, *Manual for BREEAM-SE Version 1.0*, 2013.
[21] LÅGAN, *Energi Och Miljöklassning*, 2013.

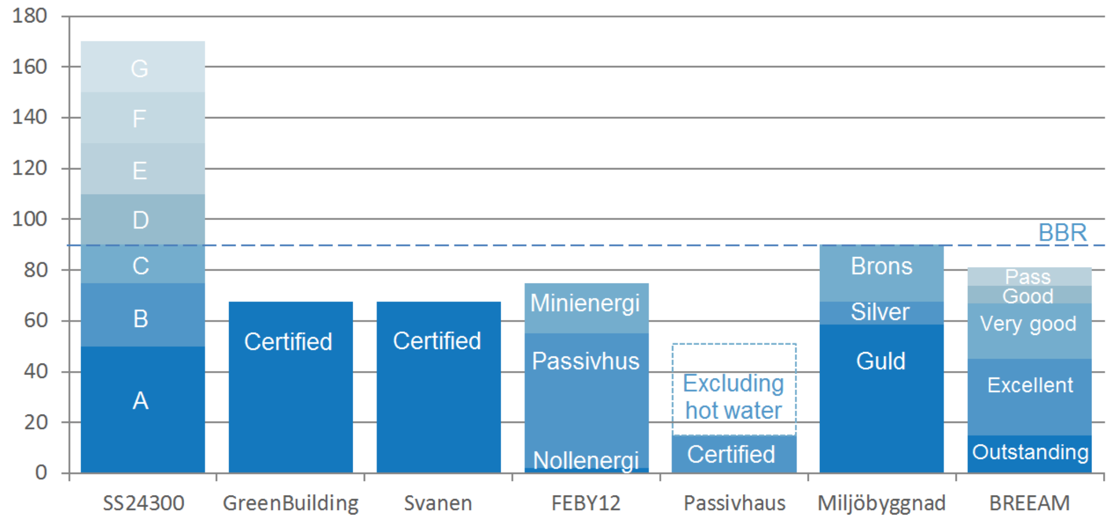



*Figure 5. Certification comparison of energy usage in multi-residential buildings in Southern Sweden.*

A growing use of ISO 14020 Type III labels, so called *Environmental Product Declaration*, *EPD* (EN15804)[22], is unlike the other types (Type I: third-party eco-logo labelling and Type II: self-declared environmental claims) using LCA to quantify the environmental impact of a material product by a third part. Development of EPD in Sweden is today supported by the Swedish Environmental Management Council *SEMCo*, which is the government's expert body on sustainable procurement. Since 1997 the Swedish building sector has in parallel used the *Building Product Declaration*, *BVD3,* formulated by *Kretsloppsrådet*[23] (today depleted). Implemented in the declarations, BASTA[24] is a commonly used environmental assessment system for prevailing non-toxic building products developed by the *Swedish Environmental Research Institute IVL* in collaboration with *Sveriges Byggindustrier*. Since BVD3s are so prevalent on the Swedish market, *IVL* has developed *BVD4* which merge the earlier EPD demands on environmental performance based on LCA calculations[25].

Currently the Swedish building sector are focusing on increased usage of product declaration and environmental certification systems mentioned in the introduction chapter. Some of them have started implementing the standardized LCA methodology, for example BREEAM-SE give points in their grading system for choices on structural materials using their own LCA calculating tool *Green Guide to Specification* (GGS), but it is also possible to hand in LCAs done in other tools approved by BREEAM[26]. The understanding in importance of performing simplified *LCA screenings* is increasing and is today a common tool for Swedish engineering firms consulting in the early design stage[27]. Reductions and limitations make the inventory research less time-consuming, but the final results yield an estimate of the environmental performance and since the results are not complete, results should be kept internally.

[22] CEN, *EN 15804:2012 Environmental Product Declarations*, 2012.
[23] Kretsloppsrådet, *BVD 3 Riktlinjer Kompl. 080404*, 2008.
[24] "BASTA", www.bastaonline.se/english/, 2013.
[25] Erlandsson, *BVD4 - Gemensamt Datakommunikationsformat För Livscykelinformation*, 2013.
[26] SGBC, *Manual for BREEAM-SE Version 1.0*, 2013.
[27] Bruzell, *Screening Avseende Klimatpåverkan Från Flerbostadshus*, 2012.

## 2.3 Life expectancy of buildings

Studying the age of the Swedish building stock[28] it is characterised of the earlier mentioned spiking of multi-residential buildings in the late 1960's, seen in Figure 6 below. Not shown in Figure 6 is the total of yearly renovations since only statistics on renovation causing change in building stock numbers are registered (yellow line) but today around 25-30 000 dwellings are renovated each year. There are demolition statistics[29] for the last 50 years where around 90-98 % has been apartments in multi-residential housing and 2-10 % single family houses. Between 1965 and 1970, of 10 000 demolished apartments on average each year, 80 % were built *before* 1920; hence 45-50 years *or longer* life span. During the year of 2006 the same comparison but built *after* 1960 was 81 %, hence 46 years or *shorter* life span. To be remembered here is that 1970 the yearly demolished part was 0,5 % of the multi-residential building stock while 2006 it had dropped to around 0,02 % yearly. Two conclusions can be drawn from this statistics. The life span of demolished buildings from the 1960's has decreased substantially but fewer buildings are demolished. The reason is caused by lowered quality in material choices, construction and maintenance. This is reasonably caused by the increased need of place to live together with the shortening of financial depreciation. The other conclusion is that the building stock is getting older more rapidly than buildings get built and demolished, renovation excluded. Hence the average building age is increasing every year.

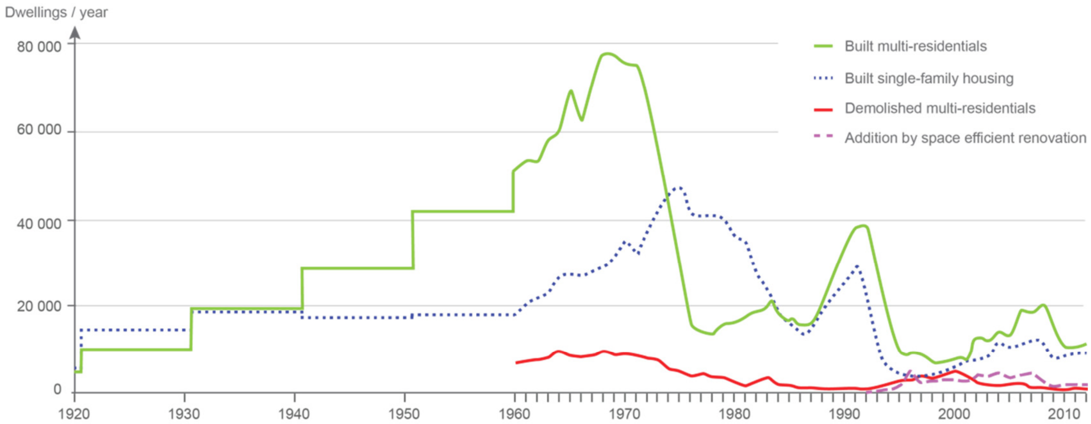



*Figure 6. New-built and demolished residential dwellings last nine decades in Sweden. Statistics from SCB.*

According to the Swedish building inspection components of building need to be maintained or changed at certain intervals to keep function[30]. The life span of a concrete foundation often survives the building above and can structurally endure more than 100 years. Plumbing and sewage pipes are usually expected to last 50 years, while the outer façade and roofing needs to be changed every 20-40 years depending on material. The gypsum boards common in wooden frames often endures the whole life span but for the LCA study a replacement rotation of 60-80 years is assumed. Shortest life spans have all mechanics for building services and home appliances which are usually replaced after 10-20 years. In the fictive scenario, shown in Figure 7 on next page, maintenance stops after 50-60 years and a worn-down and leaking envelope causes both exterior and interior moisture damages. This result in a reduced durability which ends with that the building is demolished earlier than expected.

[28] SCB, *Bostads- Och Byggnadsstatistisk Årsbok*, 2012.
[29] SCB, *Ombyggnad Och Rivning Av Flerbostadshus*, 2012.
[30] "Tekniska Livslängder För Olika Byggnadsdelar.", www.besiktningsterminalen.se/, 2014.

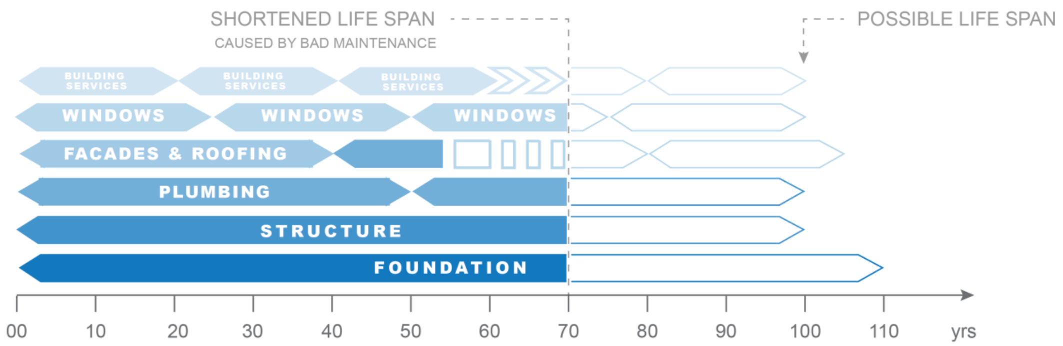


*Figure 7. Two imagined scenarios of varying life span caused by change in maintenance of components.*

To show the variation, average life span data was gathered from the American National Association of Home Builders[31], a British material cost modelling company[32], the Canadian Wood Council[33], Saga University in Japan[34], the Swiss Society of Engineers and Architects SIA[35] and the German Board of Building Standards and Regulations BBSR[36]. The frame structure's life span of these sources is arranged in order of magnitude 40, 50+, 52, 60, 65 and 100+ years for a wooden frame and 38, 50+, 60, 81, 87 and 100+ years for a concrete frame. One of the service life studies by Athena Sustainable Materials Institute showed that out of 227 demolished buildings in Minneapolis the concrete buildings had a service life of average 51 years while the wooden frame buildings lasted 79 years in average. Important for this investigation was that only 8 buildings were demolished because of structural reasons and of them only 1 building had notes of a decaying wood frame.

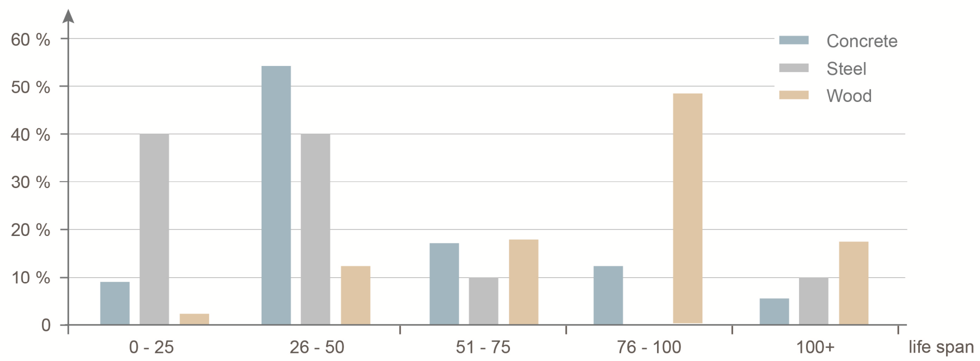


*Figure 8. Statistics on 227 demolished buildings in Minneapolis (O'Connor & Dangerfield 2004).*

Consequently it is not the technical life span of the load-bearing structure that is decisive for the length of a building's life, but rather retention of financial and social value of the property; in many cases depending on continued functionality, purpose or aesthetical appearance. Drawn from this conclusion together with earlier building stock statistics multi-residential buildings should have potential of lasting more than 100 years in Nordic climate, regardless of structure material, if constructed with good quality and maintained continuously.

[31] Seiders and Ahluwalia, *Study of Life Expectancy of Home Components*, 2007.
[32] Cost Modelling, *Building Component Life Expectancy*, 2013.
[33] O'Connor and Dangerfield, *The Environmental Benefits of Wood Construction*, 2004.
[34] Gerilla, *An Environmental Assessment of Wood and Concrete Housing Construction*, 2007.
[35] SIA, *Graue Energie von Gebäuden, Korrigenda C1 Zu SIA 2032:2010*, 2013.
[36] BBSR, *Nutzungsdauern von Bauteilen Für Lebenszyklusanalysen Nach BNB*, 2011.

# 3 Goal and scope definition

The methodology of LCA described in chapter 2.1 is in this study applied in the following four chapters. The goal and scope will start with a general and structural presentation of the case study, followed by defining functional unit, system boundaries, impact categories and allocation methods.

## 3.1 General information

As introduced in the objective in chapter 1.1 two multi-residential housing with the same overall design, but built by different contractors and in different frame materials. The house in concrete by Wåhlin Fastigheter will be named *house A* and the house in massive wood by Folkhem will be named *house B*. The houses can be seen in Figure 9 below or on the front cover. Drawings on house B are found in Appendix A.

*Table 1. General information on case study.*

| The Strandparken case study | |
|---|---|
| Location | Hamngatan, Sundbyberg (Stockholm) |
| Type, size | House A: Rental housing, 43 apartments, 3981 m² <br> House B: Tenant housing, 31 apartments, 3981 m² |
| Year of construction | 2013 - 2014 |
| Structure | House A: semi-prefab concrete system <br> House B: prefab massive wood system |

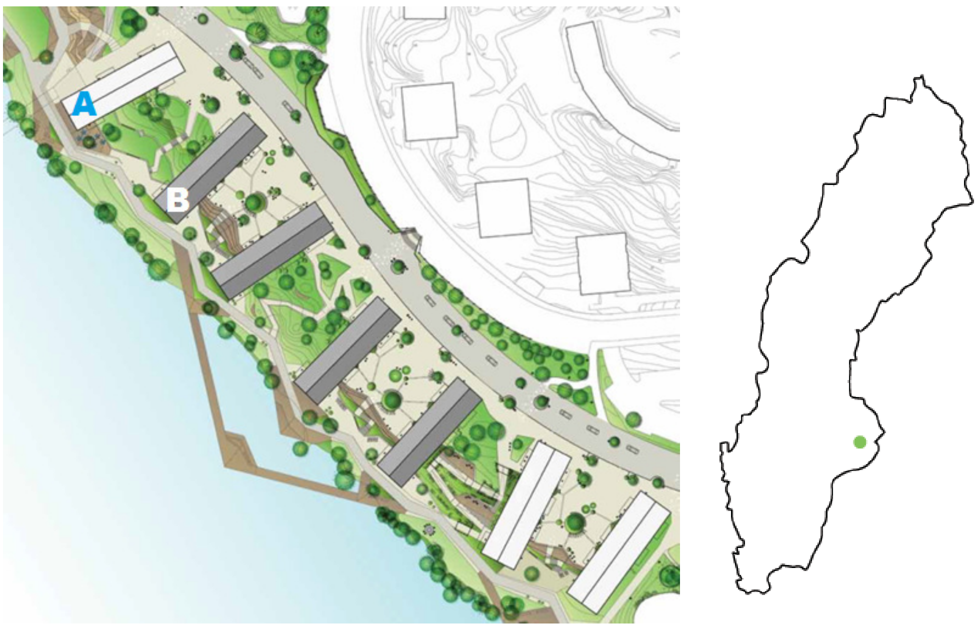



*Figure 9. Situation plan of the seven houses of Strandparken. Reservations by Folkhem.*

## 3.2 Structural information

The information off the structure of House A and B of Strandparken was gained through contact with developers and builders. Construction drawings were used to create a 3D model in Rhinoceros. For calculation of area and masses, see Appendix B. Components in *italic* are assumed negligible in the comparison of structural systems.

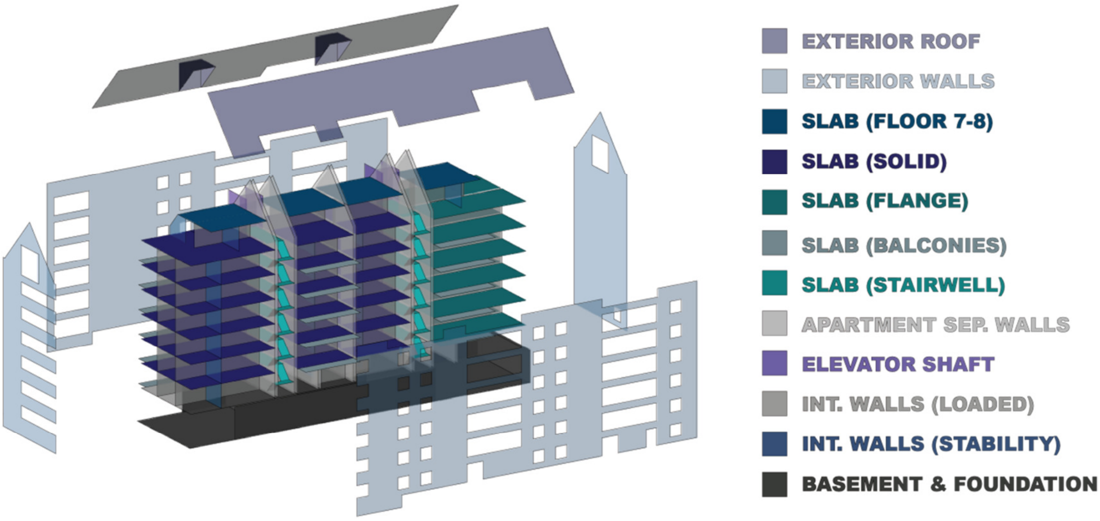



*Figure 10. Area modelling of multi-residential buildings based on construction drawings.*

### 3.2.1 House A: Prefab concrete structure

The concrete structure of house A is a half prefabricated system where thin twin walls are prefabricated with steel lattice distances. Modules are then connected to each other on site, piping and wiring drawn and finally the spacing is filled with casted concrete on site. House A is divided with one longitudinally and five transversally interior loadbearing walls. All non-loadbearing walls have been neglected.

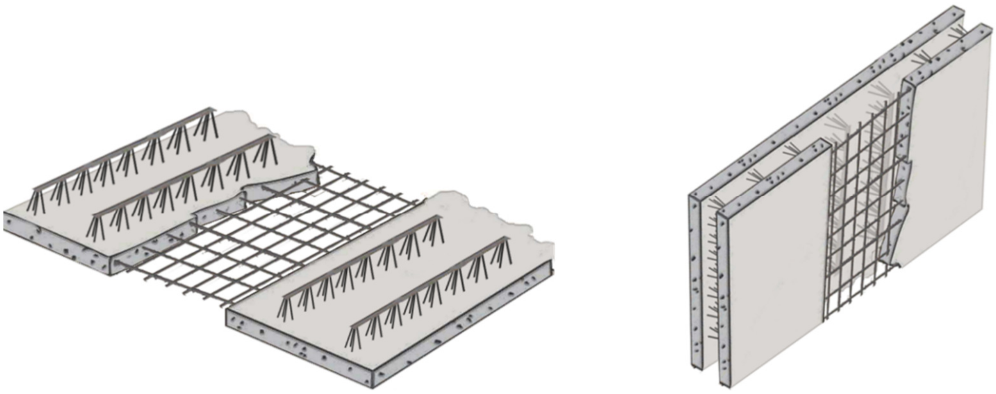
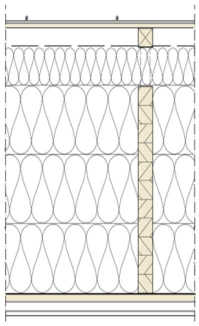
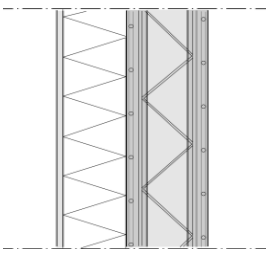
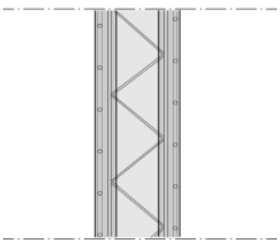
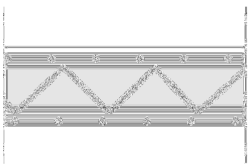
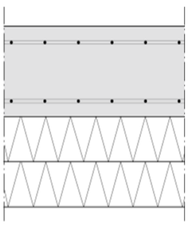


*Figure 11. Concrete semi-prefab system of house A.*

*Table 2. Concrete structure of house A. Drawings adapted from Con-Form.*

| | |
|---|---|
| **EXTERIOR ROOF 762 m²** | |
|  | *Tin roof, Underlay felt, T&G sheets*<br>45 Timber Lath 45x45 cc765<br>*Wind barrier*<br>590 Rock wool 80+3*170<br>Glue Laminated Timber 495x45 cc600<br>*PE Foil*<br>24 Plywood<br>28 Timber Lath 28x70 cc300<br>26 Gypsum Board 2*13<br>Assumed similar structure as House B |
| **EXTERIOR WALLS 1552 m²** | |
|  | *Cement Render*<br>120 Polyurethane Insulation<br>40 Prefab concrete<br>120 In-situ cast concrete<br>40 Prefab concrete<br>Steel rebar matrices 240 kg/m³ $_{\text{concrete}}$ |
| **INTERIOR WALLS 2185 m²** | |
|  | **Loadbearing Apartment separating wall**<br>40 Prefab concrete<br>120 In-situ cast concrete<br>40 Prefab concrete<br>Steel rebar matrices 240 kg/m³ $_{\text{concrete}}$ |
| **INTERIOR SLABS 3276 m²** | |
|  | **Slab In-situ filled, stairwell and balconies**<br>*Flooring*<br>150 In-situ cast concrete<br>50 Prefab concrete<br>Steel rebar matrices 240 kg/m³ $_{\text{concrete}}$ |
| **BASEMENT & FOUNDATION 1619 m²** | |
| | **Basement wall same as exterior wall.**<br>**Slab (Floor 1) same as interior slabs.** |
|  | **Ground foundation**<br>300 In-situ concrete<br>Steel rebar 40 kg/m³ $_{\text{concrete}}$<br>*EPS Polystyrene*<br>*Macadam* |

### 3.2.2 House B: Massive wood structure

The cross laminated timber structure of House B is a prefabricated system. House B is a tenant housing of 3981 m² with 31 apartments and 2 premises, transversally (and in northwest longitudinally) divided with five apartment separating walls which consists of two modules joined together. In the middle and South West part the apartments are longitudinally supported by two interior loadbearing walls and some interior walls, seen in to the left in Figure 10. The elevator shaft is also made by a CLT structure, but all walls are anchored through steel rods tensioned down into the concrete basement.

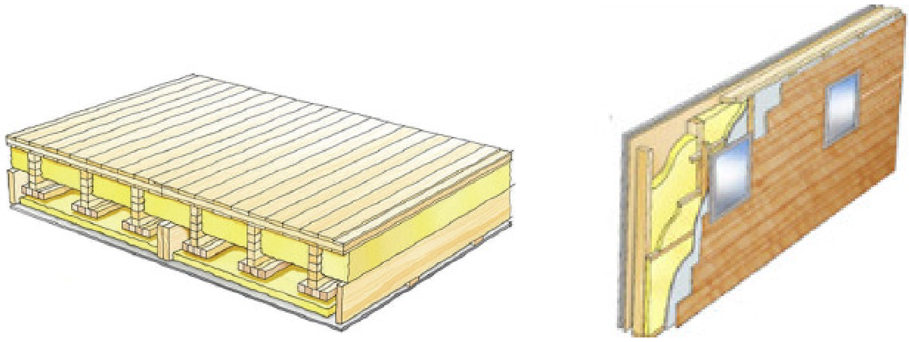
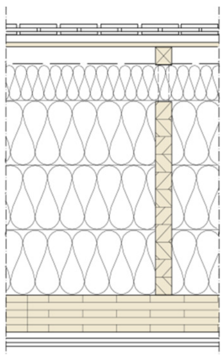
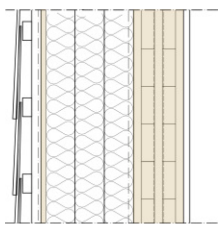
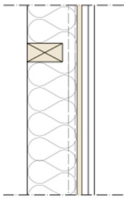


*Figure 12. CLT prefab system of house B.*

*Table 3. Massive wood structure of house B. Drawings adapted from Martinsons.*

| **EXTERIOR ROOF** 762 m² | |
|---|---|
|  | <u>828 mm</u><br><br>*Cedar chips*<br>*Timber lath &*<br>*Underlay felt*<br>12 Plywood<br>45 Timber Lath 45x45 cc765<br>*Wind barrier*<br>590 Rock wool 80+3*170<br>Glue Laminated Timber 495x45 cc765<br>*PE Foil*<br>95 CLT massive wood board<br>28 Timber Lath 28x70 cc300<br>26 Gypsum Board 2*13 |
| **EXTERIOR WALLS** 1552 m² | |
|  | <u>420 mm</u><br>*Cedar chip, lath, studs, wind barrier*<br>12 Plywood lath 12x70 cc600<br>210 Rock wool 3*70<br>Timber studs 2*70x45 cc600<br>*PE foil*<br>120 CLT massive wood board<br>15 Gypsum Board<br><br>Post-tensioned steel rods 9* ø20<br>Steel pillars (VKR) 6* 100x100<br>Glulam pillars 14* 240x120 |

## INTERIOR WALLS 4482 m²

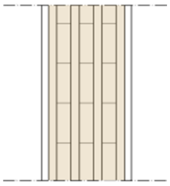


**Apartment separating wall LS-07-04**

30 Gypsum board 2*15
12 Construction Plywood
120 Rock wool
Timber studs 45x120 cc600

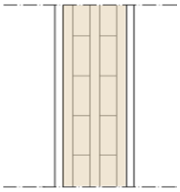
Similar mirrored or meeting IV-03-03 air gap 20

Post-tensioned steel rods 36* ø20



**Loadbearing interior wall IV-03-04**

15 Gypsum board 15
170 CLT massive wood board
15 Gypsum board 15

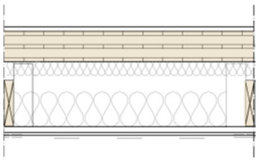


**Interior wall IV-03-02 & IV-03-03 (Elevator shaft)**

15 Gypsum board 15
120 CLT massive wood board
15 Gypsum board 15

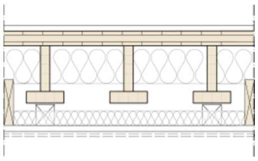
Post-tensioned steel cables 12* ø20

## INTERIOR SLABS 3276 m²



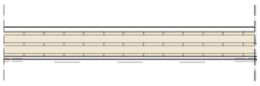
**Slab MBK-03-02**

*Flooring*
145 CLT massive wood board
240 Rock wool 70 + air + 170
Module edge timber studs 220x45 cc600
26 Gypsum board 2*13



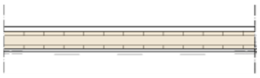
**Slab MBK-03-02 (Towards Hamngatan)**

*Flooring*
70 CLT massive wood board
240 Rock wool 170 + air + 70
GLT beams w220x45, f56x180 cc400
Module edge timber studs 220x45 cc600
26 Gypsum board 2*13



**Slab MB-03-04 (floor 7-8) & Slab balconies**

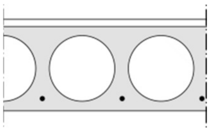
*Flooring, Floor heating*
170 CLT massive wood board
26 Gypsum board 2*13



**Slab stairwells (Incl. area of stairs)**

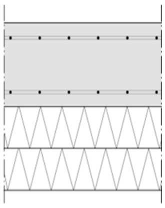
*Flooring*
120 CLT massive wood board
26 Gypsum board 2*13

## BASEMENT & FOUNDATION 1619 m²



**Slab Hollow core concrete (Floor 1)**

*Flooring*
200 Prefab concrete
Steel rebar 65 kg/m³ $_{concrete}$



**Ground foundation & Basement wall**

300 In-situ concrete
Steel rebar 40 kg/m³ $_{concrete}$
*EPS Polystyrene*
*Macadam*

## 3.3 Functional unit

As the comparison between structural frames also has to be equal according to all functions as acoustics, heat losses, and fire resistance the LCA comparison has to include added materials to get similar structural properties. Today it is fully possible to achieve similar functionality with a wooden structure as a concrete alternative. Regarding to fire resistance there is regulations in fire resistance classes which usually results in wood treatment or interior plasterboards. Adding to that, the regulations that for buildings built with a wooden façade higher than two storeys a residential sprinkler system has to be added. To achieve the same acoustical properties special techniques such as detached gypsum boards in ceiling are used to reduce footfall and structure-borne noise.

For equitable comparison the functional unit is chosen to be "global warming potential by GHG emissions in kg $CO_{2,eq.}/m^2$ of liveable area" of "the structural wooden frame of house B of Strandparken, including material components to equal the functional properties of house A" compared to "the concrete structure of house A of Strandparken". That means that some of the non-structural construction, e.g. façade, windows, elevators, bathrooms, flooring, finishing and non-loaded interior walls not are included in the LCA comparison.

## 3.4 System boundaries

To close the topic into an achievable time frame some mayor system boundaries were set. Social, cultural and economic aspects for sustainable overview will be breached to the advantage of environmental and technical factors. The system boundary is comprised of the building materials whole life cycle, also taking into account reforestation and operational heating, seen in Figure 13 below.

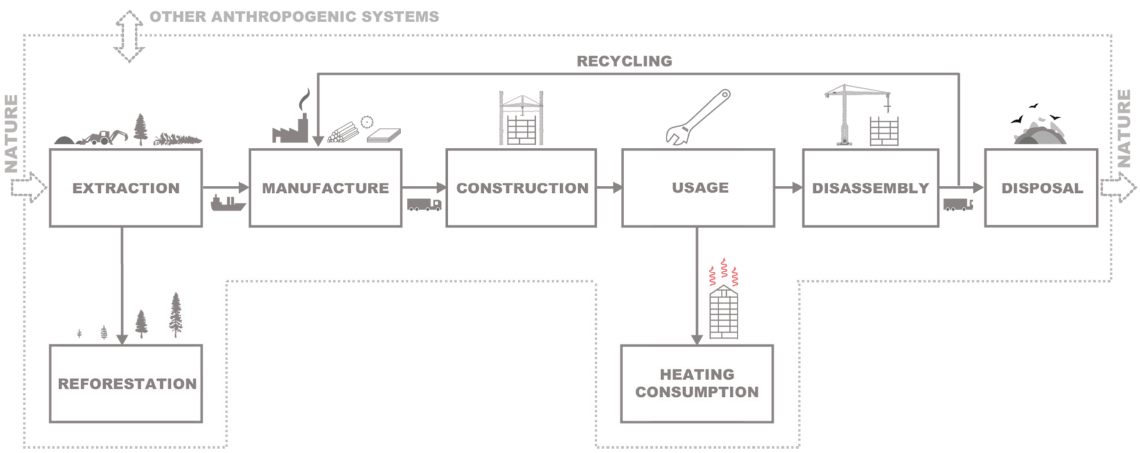



*Figure 13. System boundaries of the cradle-to-grave case study LCA.*

House A consists of rental units with more apartments than house B in total and thus different planning. To adjust to the functional unit some assumptions were done, e.g. the interior non-loadbearing walls are neglected. The correction of the polyurethane insulation thickness in the concrete exterior walls is done so that both structures keep the same thermal conductivity and equal heat demand is assumed. Difference in thermal bridges, air leakage and decrease of functionality of insulation materials is excluded in this study. Also the waste production during construction is neglected because of most modules are prefabricated.

Thermal inertia of the concrete is neglected since it for current building code is shown that the operational heating savings (including tap water heating and ventilation electricity) for thermal mass in a concrete structure instead of wood is less than 1 %[37].

## 3.5 Impact categories

As earlier mentioned the impact of GHG emissions in the Swedish building sector the other phases than heating is increasing. GHG emissions are used to calculate the *global warming potential (GWP)*[38], but there are several other categories for total environmental impact, e.g. acidification, eutrophication (plankton blooming and hypoxia), land and resource usage, human toxicity and cumulative energy demand (CED). Because of lack of time in gathering data, together with the delimitations of the questions at issue, the focus of this study will only regard global warming through GHG emissions. If gathered data on in the construction stages only can be found in cumulative energy it will be translated to GHG emissions based on Swedish energy production. The other impact categories will be outside the scope of the assessment. Therefore this study should be seen only as a screening LCA not showing all impact categories weighted together. Also to be remembered is the functional unit, which limit the focus on the frames and not the impact of the whole house.

## 3.6 Allocation methods

Allocation is of interest when several products share the same process and environmental loads need to be partitioned. To avoid allocation complications certain processes will be subdivided, for example electricity production will be a separate process for each construction stage and within the production stage for each material. Also the carbonatation of concrete will be subdivided to the usage and end of life stage separately. All scrap in the wood production will be allocated as incineration with energy recovery but the energy will not be connected to be used in the production, but instead treated at its own subdivision. In reality this may not be the case but it is treated separately to be able to see its impact. The recycling of materials in the end of life stage will though be reconnected to the production stage according to data on proportion of recycled material in new production. Other options as reuse, downcycling through refurbishment, or landfill will be further discussed in chapter 4.1.4 and chapter 6.

[37] Dodoo, et al., “Effect of Thermal Mass on Life Cycle Primary Energy Balances”, 2012.
[38] UN IPCC, *Fourth Assessment Report, Working Group I: Chapter 2*, 2007.

# 4 Life Cycle Inventory

The systems flow model of each house is built up using the different stages and system boundaries shown in Figure 13 in chapter 3.4 on page 16. The quantifying of material shown in previous chapter was used as the base of calculating volumes and masses which then were inserted in the LCA software and database GaBi.

## 4.1 LCI - House A: Concrete structure

The inventory of the wooden frame structure in House A was collected using both predefined datasets in GaBi and where there was shortage of data some assumptions had to been done, which all are found in the following subchapters. When Swedish material production data couldn't be found existing European or American data in GaBi or ELCD was used, but using Swedish conditions to the greatest extent, e.g. electricity used was generated by the real national average energy mix of mainly biofuels, oil, hydro and nuclear power.

GaBi contained pre-set full datasets for different types of material merged into single components, but the wood processing had to be built up using components for each step (including growth of seedlings, plantation, harvesting, debarking, sawing, laminating and reforestation). Therefore as an example the concrete production takes less space in the flow model diagram, which is not proportional with environmental impact of the components. The width of the arrows is in this case indicating mass differences of the considered processes.

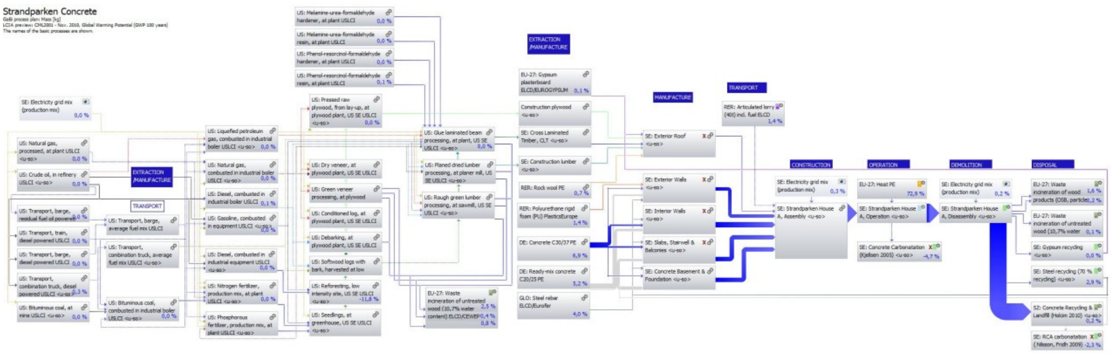



*Figure 14. Life Cycle Inventory Model of House A in GaBi LCA Software (Close-up found in Appendix C).*

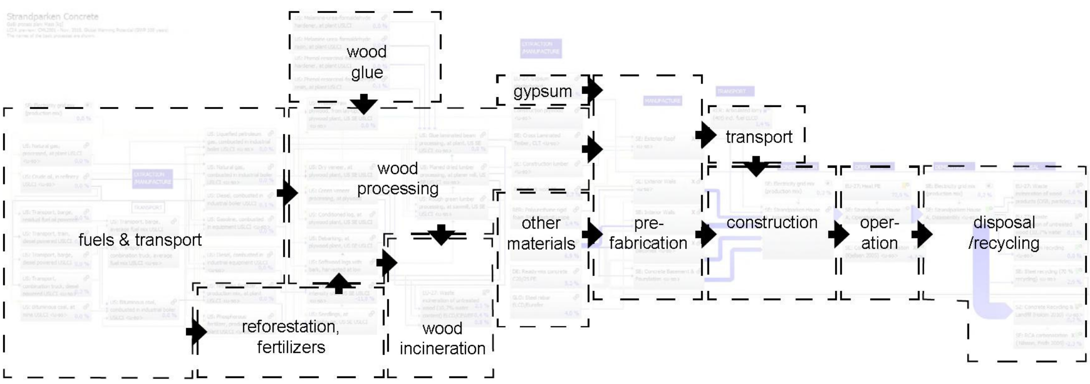



*Figure 15. Simplified flows in LCI model of house A.*

### 4.1.1 Manufacturing

Concrete is a material varying in composition. For 1 m³ concrete for buildings of the normal strength class C25/30 it takes approximately 2000 kg aggregate of fine and coarse gravel, 350 kg cement, 1 kg of admixtures, 180 litres of water and in energy 7 litres fuel oil or diesel and 15 kWh electricity[39]. But most decisive for the carbon and primary energy footprint is the cement production where 40 kg coal and 40 kWh of electricity is used to produce 400 kWh of heating, which is needed for the calcination process when limestone is burned to produce the binder calcium oxide in rotating furnaces. When the cement clinker is mixed with the water and aggregates the concrete cures and the cement paste is hardened through hydration which calcium hydroxide is formed. Production of 1 tonne pure cement (*Portland CEM I*) is emitting around 800 kg $CO_{2,eq}$ whereof 64 % derives from the calcination reaction[40]. In house A approximately 3 650 tonnes concrete with 530 tonnes building cement (*CEM II*) is used, which equals an emission outlet through cement calcination of 250 tonnes $CO_{2,eq}$. The sandwich concrete elements of Con-Form are half prefabricated with C30/37 in Töcksfors in the Middle West of Sweden. The material transport of these elements to Sundbyberg is 636 571 tonnes x km by truck (see calculations in Appendix B). Although the distance is shorter than for the prefab wooden modules the weight is more than double. The in-situ casted concrete is assumed to have aggregate and cement extracted in the Stockholm region and is, together with the roof structure, therefore neglected.

### 4.1.2 Construction

Construction time is approximately the same for both structures though more energy is used for the concrete construction because of the in-situ cast concrete and heavier lifts. The structure of House A (1 700 tonnes) weights more than double of the structure of House B (4 000 tonnes). The value of 160 MJ/m² used for the concrete house erection in SP's report is assumed lower, 140 MJ/m², since 35 % of the concrete is prefabricated which demands less energy consumption. he roof structure is assumed the same as the wooden construction. The wall insulation thickness is adjusted in House A so heat losses would be approximately equal for both structures.

*Figure 16. Construction of House A in prefab concrete twin walls and plate slabs (Boetten, 2013).*

[39] Gillberg, *Betong och miljö*, Betongforum 1999.
[40] Kjellsen, et al., *The CO2 Balance of Concrete in a Life Cycle Perspective*, 2005.

### 4.1.3 Carbonatation

When concrete ages the calcium hydroxide converts into calcium carbonate, named *carbonatation* (in some research referred to as *carbonation*). Though the process is strengthening the concrete it also lowers the pH which can cause reinforcement bars to corrode and accelerate the degradation of concrete. The carbonatation rate is depending on several factors, such as concrete density, type of binder, exposure area, concentration of $CO_2$ in surrounding air, and degree of hydration. A water supply will cause *leaching* which slows down the carbonatation process. The optimized climate for carbonatation is high temperature and relative humidity between 60 and 80 %. Interior uncovered concrete carbonates four times faster than weather exposed concrete[41]. The carbonatation reaction absorbs carbon dioxide and calcium carbonate is reformed, the opposite reaction of the combination of cement calcination and concrete hydration. Theoretically all concrete can be carbonated, however because of the ratio of calcium oxides bound to silicon dioxides and silicate hydrates in Swedish concrete (CEMII > 65 % Portland clinker), 25 % of the concrete is likely to remain non-carbonated[42].

### 4.1.4 End of life

In Sweden 2010 around 70 % of all demolished concrete rubble was used as *Recycled Concrete Aggregate*, *RCA*, and the rest went to landfill. After the concrete rubble is crushed to RCA at plants and stockpiled between 2 weeks and 4 months (neglected in the LCA), 90 % of the RCA is being put below ground as road fillings, 6 % to gravel paving and 4 % is recycled into concrete again [43].

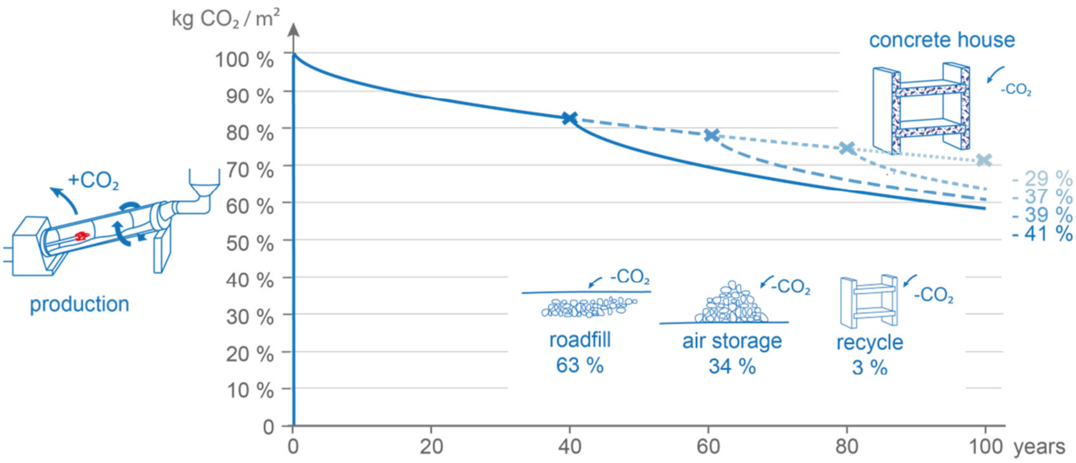



*Figure 17. Carbon footprint of concrete life-cycle with carbonatation difference of varying end use.*

Numbers on the recycling process of concrete is missing in the GaBi database and is instead replaced by measurements from the Swiss cement supplier Holcim[44]. These includes crushing, load and unload but excludes transport and claims a cumulative energy demand of 63,4 MJ and carbon footprint of 1,5 kg $CO_{2,eq.}$ per tonne aggregate. To put this in perspective the numbers on conventional aggregate production for an average of four of their plants is 68,1 MJ and 2,7 kg $CO_{2,eq.}$ per tonne aggregate and add to this the negative environmental impact in land excavation and resource use of crushing natural aggregate.

[41] Ibid.
[42] Engelsen, "Carbon Dioxide Uptake in Demolished and Crushed Concrete.", 2005.
[43] Kjellsen, et al.,"The CO2 Balance of Concrete in a Life Cycle Perspective.", 2005.
[44] Holcim AG, "Ökobilanzen Rezyklierter Gesteinskörnung Für Beton.", 2010.

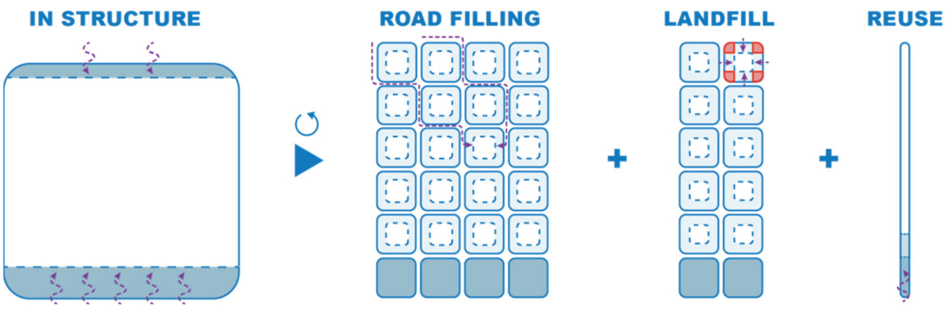



*Figure 18. Calculation of carbonatation during operation and various use of Recycled Concrete Aggregate.*

The end use alternatives differ in carbonation rate. A concrete exposed to exterior air has a carbonatation rate twice as fast as a wet concrete and 50 % faster than buried concrete. An interior placed concrete carbonates even quicker, around 4 times quicker than the exterior exposed one, because of keeping the concrete pores dry but still keeping the optimal relative humidity (60-80 %) for the carbonatation reactions. Even more important as the surrounding conditions is the exposure area since that one becomes around 50 times bigger for crushed concrete since the average aggregate size has a diameter of approximately 12 mm (based on Danish RCA)[45] . The equation for carbonated concrete is following:

$$Volume\ carbonated = Exposed\ area\ \cdot carbonation\ rate\ \cdot \sqrt{years} \qquad (Eq.\ 1)$$

The results of the concrete carbonatation for the variation of life spans and end of life can be seen in Figure 17. Below in Figure 19 the GHG emissions of cement calcination and carbonatation is shown proportional to the total production stage.

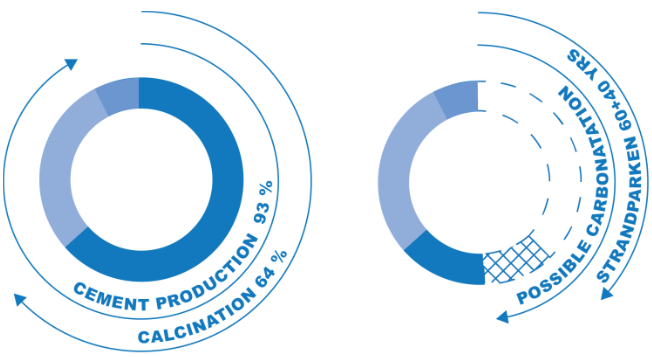



*Figure 19. GHG emissions during concrete production (C30/37, CEM II) and possible carbonatation.*

In Sweden today approximately 50 % of all building demolition waste is reused or recycled with a governmental goal[46] of 70 % to 2020 and this number has been assumed for steel recycling. After the reinforcement has been separated it can be recycled in an electric arc furnace with a third of the primary energy required steelmaking from ore using a blast furnace. The emissions are even less; 0,4 kg compared to 1,6 kg $CO_{2,eq.}$ per kg steel[47].

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[45] Kjellsen, et al., "The CO2 Balance of Concrete in a Life Cycle Perspective.", 2005.
[46] Naturvårdsverket, " Sveriges Avfallsplan 2012-2017.", 2012.
[47] WellMet2050, "Steel and Aluminium Facts.", 2009.

## 4.2 LCI – House B: Massive wood structure

The inventory of the concrete structure in House A was gathered the same way and with the same system boundaries as for house B. Transport of material and building components were separated in the stages of manufacturing and construction. Worth mentioning is that the concrete walls in house A only consists of one module while two joined CLT wall modules form the apartment separating walls in house B; therefore more wall area.

The inventory model shown below is showing components containing single- or multi-data processes connected with flow arrows, in this case showing mass. For intelligibility a simplified version is shown below. As the same issue as for the LCI flow model for house A the wood processes are built up part-by-part but the mass flow arrows indicate that wood has a bigger proportion in this house (510 tonnes of construction wood compared to the reinforced concrete foundation of 800 tonnes). Even though it is not a concrete structure the concrete in the foundation has a great impact on the LCA results.

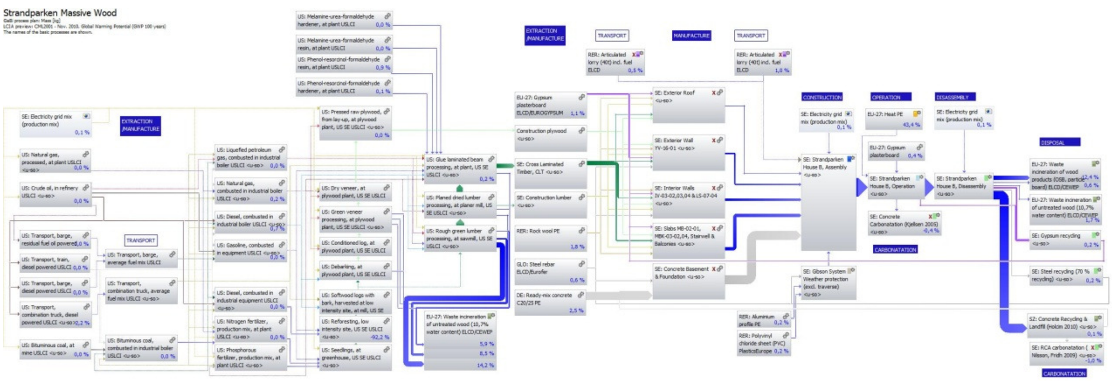


*Figure 20. Life Cycle Inventory model of house B in GaBi LCA Software (Close-up found in Appendix).*

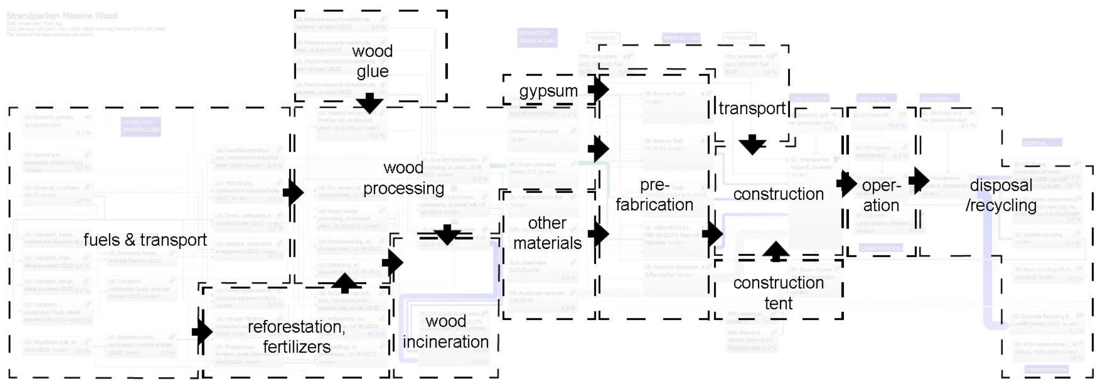


*Figure 21. Simplified flows in LCI model of house B.*

### 4.2.1 Extraction and manufacture

The wood used for the construction in this case study is more or less Nordic Spruce, mainly in the CLT boards but also for the plywood, beams and lath. Other wood species are outside the system boundaries (flooring in ash, window frames in pine, façade in cedar chips). Looking at the forest volume of Sweden 3000 Mm³ (2012) has an annual gross felling of 85 Mm³/year (-3%) and a forest increment of around 120 Mm³/year (+4%)[48]. Hence the Swedish forest volume is growing and possibilities of increasing use of lumber for construction exists, though harvesting should be done wisely respecting old primeval forests, recreation areas, wildlife and national reservoirs. Looking at softwood in Sweden it is harvested after 90-120 years, since growing rate reach equilibrium after 100 years, decaying and growing in the same rate.

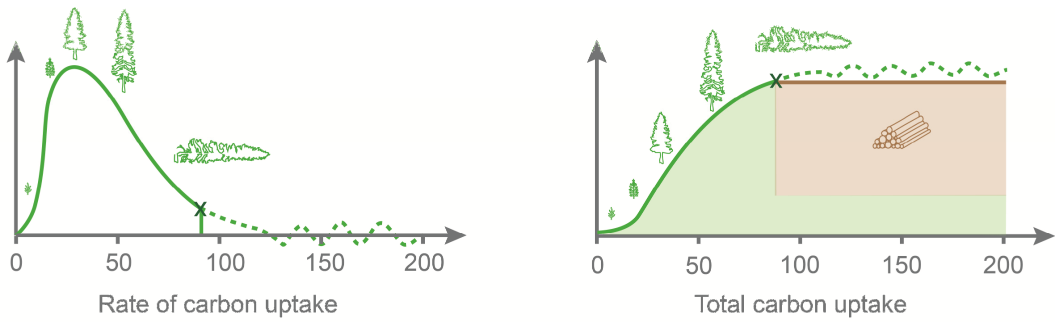


*Figure 22. Instantaneous and cumulative carbon uptake for Nordic spruces with harvesting at 90 years.*

Interesting for harvesting is that the stem of the tree is just over half of the biomass. The rest becomes paper pulp, gets combusted as biofuels or is left on site. Almost all wood, including wood scrap during manufacturing stage, eventually goes to *incineration*, meaning that the wood is combusted with energy recovery. At the same time its stored *biogenic carbon* is emitted to the atmosphere, a part of the *carbon sequestration cycle*, further described in chapter 6.


*Figure 23. Average distribution of biomass in 100-year old Nordic softwood trees.*

The climate impact of the extraction stage consists of the whole reforestation period, including seedling growth in greenhouses, distribution, planting, thinning, harvesting and transport of timber. Following is the processing of fabrication in sawmills, where timber logs are debarked, sawn, sorted, dried and packed to be dispatched to construction sites. Inventory quantities are collected using GaBi datasets with refinement of timber into lumber, plywood and CLT boards, including machinery fuels, lamination glue and fertilizers for seedlings. To verify that the datasets are equal with the CLT production by Martinsons, comparison has been done with the Swedish EPD on CLT made by the Swedish Environmental Research Institute, IVL[49].

[48] Skogsstyrelsen, “Skogsstatistiska Årsboken”, 2013.
[49] Erlandsson, “Byggvarudeklaration BVD3 Korslimmat Trä KLT”, 2009.

### 4.2.2 Construction

After being prefabricated the massive wood modules were transported from Bygdsiljum North of Umeå in Sweden, down to Sundbyberg outside Stockholm, which is an unusually long distance (705 km) for prefabrication. Tyréns estimated in their LCA screening a total material transport of 838 000 tonnes x kilometres by truck, where the prefabricated modules from Bygdsiljum to Stockholm is more than a third of that (approx. 304 560 tonnes x km). In the LCA results the transport distances has been split so the later belongs to the production stage. Since the wooden modules are relatively light this impact isn't that significant which will be seen later in the Impact Assessment in chapter 5.

The assembly of multi-residential buildings with prefabricated elements is a fast process and wooden elements have the benefit of relatively light lifts for the cranes. For the first wooden structure house in Strandparken, after the concrete foundation and basement were cast, a new floor was raised every 2 weeks except the final two floors with the roof modules which took 6-7 weeks, which in total is similar to the neighbouring construction with prefabricated concrete[50]. However, a wooden structure like this demands weather protection and therefore a height-adjustable tent was used, which besides moisture control give advantages like healthier and safer working environment. For the climate impact of using a construction tent it is for the LCA assumed that the rentable tent from Hallbyggarna Jonsered[51] is reused 20 times, the PVC textile (600 g/m²) is changed once and the light weight steel structure (8 pillars of 30 m, traverse excluded) and aluminium truss bays (10 kg/m²) of approximately 10 respectively 6 tonnes is recycled afterwards.

*Figure 24. House A in construction without protection. House C next to B raised with height-adjustable tent.*

For calculation of the carbon emissions for the construction activities there is a lack of data for Strandparken and instead the energy demand value of 60 MJ/m² (16,7 kWh/m²) used in the study by SP[52] (derived from Björkman & Tillman, 1997) has been used. For this value some excluded processes are ground works, storage heating, transport within the site, and temporary facilities for personnel. Since the main part of components is prefabricated modules, some energy of assembling of modules in manufacturing is allocated in construction and also material losses during the construction phase are small and therefore neglected.

[50] Karlsson, Site Manager at Folkhem, interviewed 2013-10-10.
[51] Hallbyggarna-Jonsereds, "Gibson Tower product sheet", 2013.
[52] Eriksson, et al., *Life Cycle Assessment of Different Building Systems*, 2013.

### 4.2.3 Usage phase

The operatioaln stage is usually the most dominating in life cycle studies of buildings because of the energy usage by people. The energy usage per year of heating indoor air and warm water in the Swedish multi-residential building stock is in average of 144 kWh/m²$_{Atemp}$ and 120 kWh/ m²$_{Atemp}$ for new production (2001-2011) including all heating methods[53]. The two buildings are designed to have roughly equally large heat losses ($U_{wall}$ = 0,16 W/mK) and has been calculated by Tyréns to 75 kWh/ m², $_{Atemp}$ yearly. Difference in heated area $A_{temp}$ and measured living area used for the LCA calculations is neglected.

Included in the operation phase and relevant to the life expectancy is the maintenance. This work is always hard to calculate in beforehand because of the craftsmanship and more or less serious construction errors than can occur. SP calculated in their report the carbon footprint for massive wood element version the all-over maintenance phase (25,9 kg $CO_{2,eq.}$/m²) to be more than twice of the construction process (10,9 kg $CO_{2,eq.}$/m²). This maintenance is though less than 5 % of the operational energy use (587,0 kg $CO_{2,eq.}$/m²). But for this case study the functional unit is limited to the frame structure which makes the maintenance much less significant. For the wooden frame the only maintenance assumed is the gypsum boards where the replacement of 40-80 years is used for maintenance, which for a building span of 60 years means that 50 % is assumed to need to be replaced. The worn out gypsum board is recycled and in the flow model allocated back to production.

### 4.2.4 End of life

After decades of decay with lack of maintenance a building could reach the stage of becoming no longer economically viable for the building administrators to keep. If the proper function or appearance of the building can't be kept or developers find better use of the land, the building usually gets demolished. For a massive wood prefab structure like the one in Strandparken there is financial potential of the wood to be reused but the modules then have to be disassembled the inverse way of assembly. This procedure could be seen more time-demanding but decreases the amount of waste and simplifies the separating of modules into reusable or recyclable components. After disassembling choices of disposal are reused as a downcycled product, landfill, or wood incineration. For the LCA wood incineration of 90 % of the disposal is assumed, but the other options are regarded in the sensitivity analysis in chapters 6.1.2.

Gypsum boards have the history of going to landfill in Sweden but since April 2012 regulations from *Naturvårdsverket* (Swedish Environmental Protection Agency) have become stricter and today all demolished gypsum must be recycled which has led to 25 % of gypsum production today coming from recycled waste[54]. The amount of emissions created during the recycling process is approximately 0,07 kg $CO_{2,eq.}$ / kg gypsum board[55]. For the other materials recycling of insulation has been neglected in both buildings. The concrete and reinforcement steel are segregated the same way as for house A, and added to the steel recycling are the post-tensioned steel cables.

[53] Energimyndigheten, *Energistatistik För Flerbostadshus*, 2012.
[54] Gips Recycling Sverige AB, "Återvinning gipsskivor", www.gipsrecycling.se/, 2013.
[55] US Environmental Protection Agency, *Drywall*, 2012.

# 5 Impact assessment results

As mentioned about impact categories in chapter 3.5 only GHG emissions will be presented of the results produced in the LCA using the GaBi software. Using the pre-set GWP model, which is the model adopted by IPCC, results are presented, first excluding, then including wood incineration and the forest sequestration cycle. Concluded in chapter 2.3 the life span of buildings is in most cases not dependent on the structure but the life span is still relevant for results regarding operational usage, maintenance, time frame and disposal times.

## 5.1 Results by life cycle phases

The results will be presented in a systematic order starting in Figure 25 where the LCA comparison excludes heating in the operation phase and the forest sequestration cycle. Notable is the large impact of the extraction and production stage where emissions for concrete house A is 27 % larger than for wooden house B, mainly caused by the concrete production. Interesting is that when including the concrete carbonatation during operation and disposal the production relation is the opposite. Also noted is that the reinforcement steel gives a large impact though 70 % is assumed recycled and allocated in the end stages.

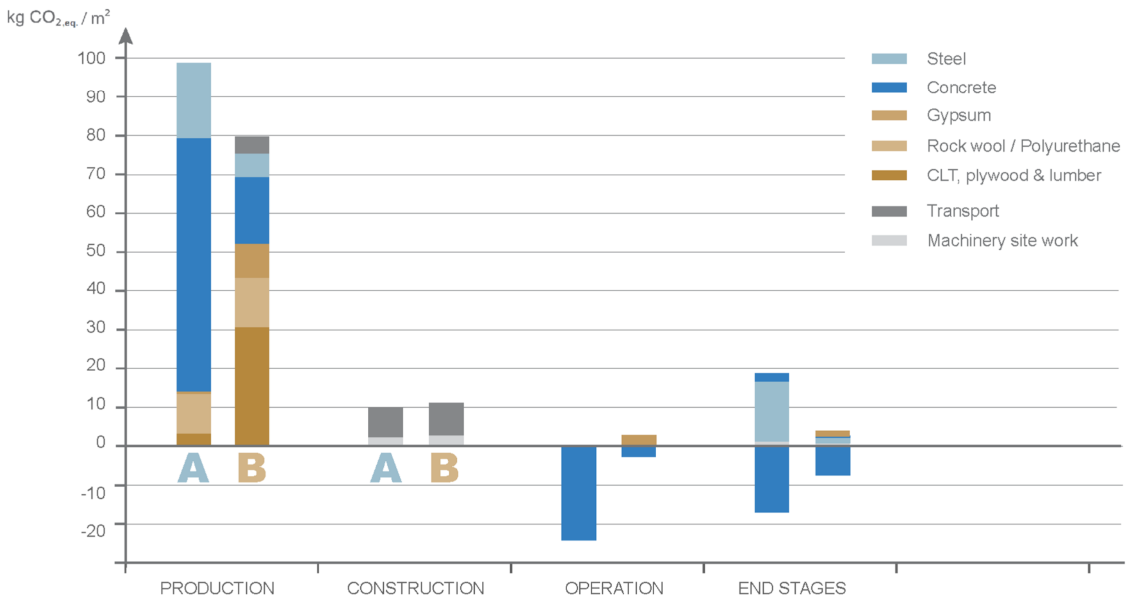


*Figure 25. LCA house A vs. B for 60 maintenance + 40 disposal years with limited system boundaries.*

In Figure 26 the system boundaries are extended to include the carbon sequestration through reforestation for 90 years, together with the wood incineration, seen as an emission to the IPCC model where 1,6 kg of $CO_2$ is emitted for each kg of incinerated wood. But at the same time the biofuel for energy production works as a substitution of fossil fuels, which can be seen as a negative GWP.

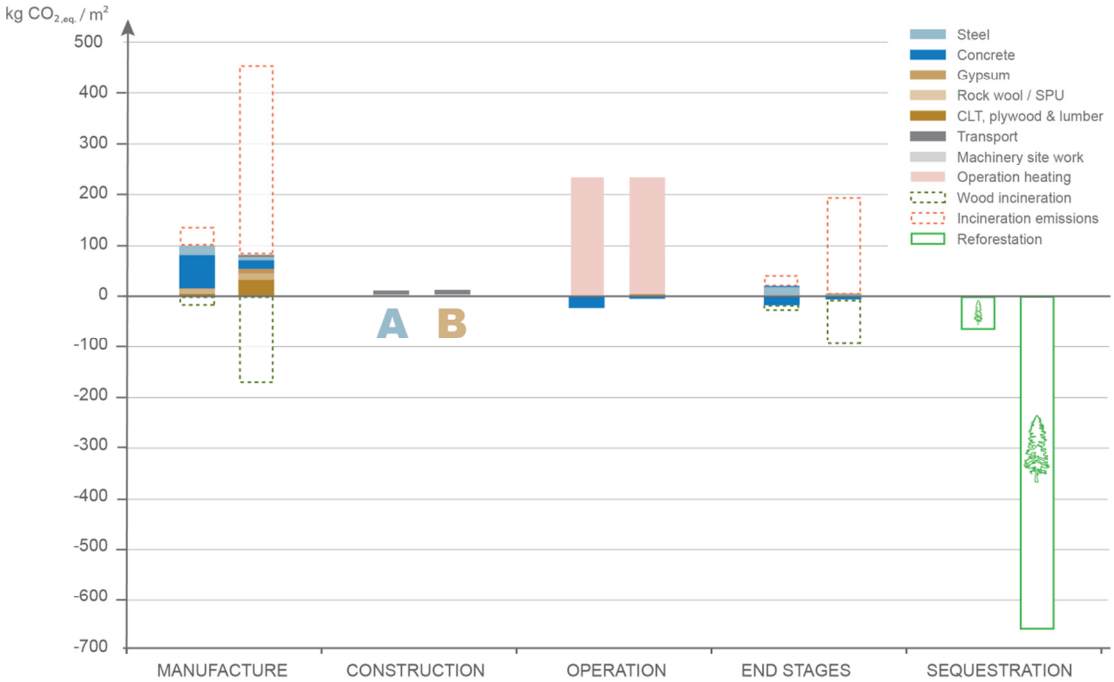


*Figure 26. LCA for 60 + 40 years including heating, wood incineration and biogenic carbon cycle.*

The results are then compared in Figure 27 with the LCA study by SP where the fossil fuel substitution and incineration emissions are replaced to match SP's categories. The large difference in the manufacture and disposal stages can be derived to the functional unit where SP includes all components of a 4-storey *house* instead of only an 8-storey *frame structure*, hence less energy intensive materials per liveable area. The difference in operational heating is because Wäludden is an older house with less insulation. The difference in wood incineration and sequestration is though so large that this is analysed further in chapter 6.1.1.

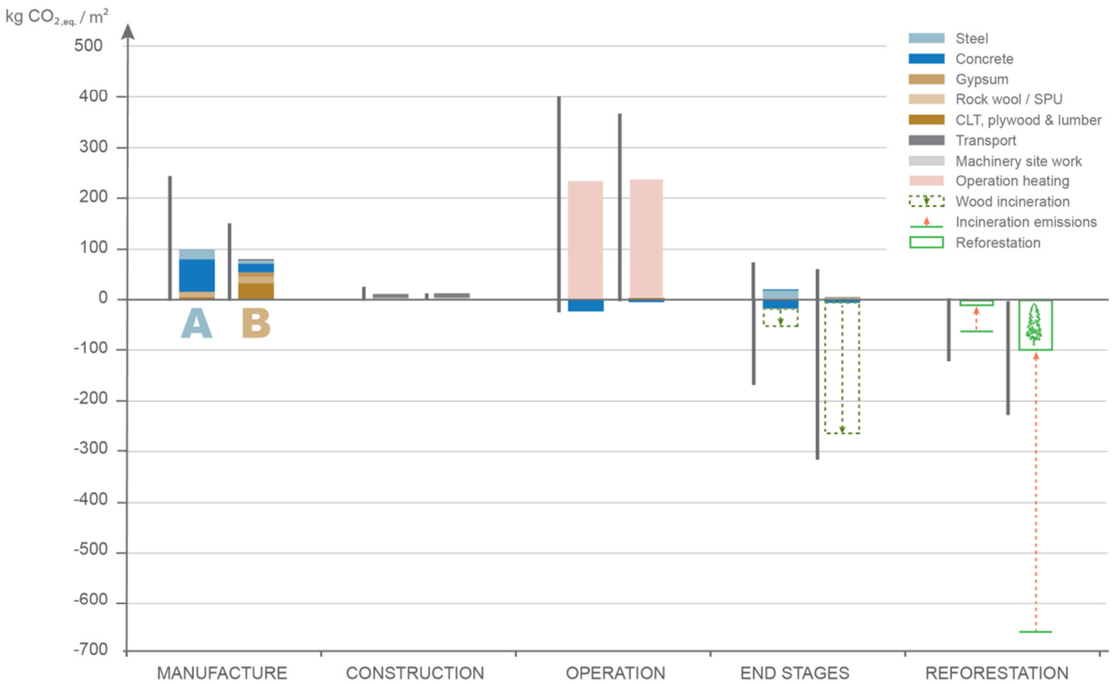


*Figure 27. Comparison with an LCA study (SP 2013) including fossil fuel substitution of wood incineration.*

## 5.2 Total results by life span variation

For the total LCIA results a variation in life spans of 40, 60, 80 and 100 years has been studied, still with a fixed time horizon of 100 years. In Figure 28 the system boundaries are limited coherently to the case of Figure 25 but including heating. Here it is shown that including the concrete carbonatation but excluding the biogenic carbon cycle the concrete structure still has a larger carbon footprint. If the combustion of wood as fossil fuel substitution would be disregarded, the results would be near to equal. In Figure 29 all the rest wood during production also is incinerated.

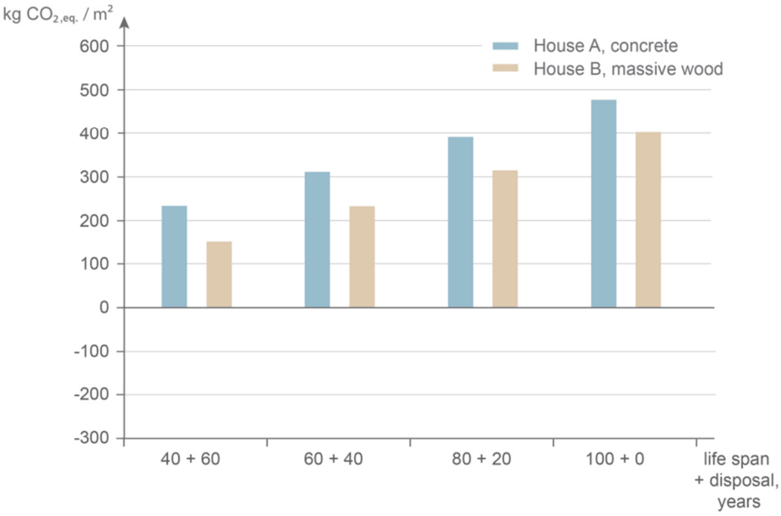


*Figure 28. LCA with varying service and disposal life with limited system boundaries.*

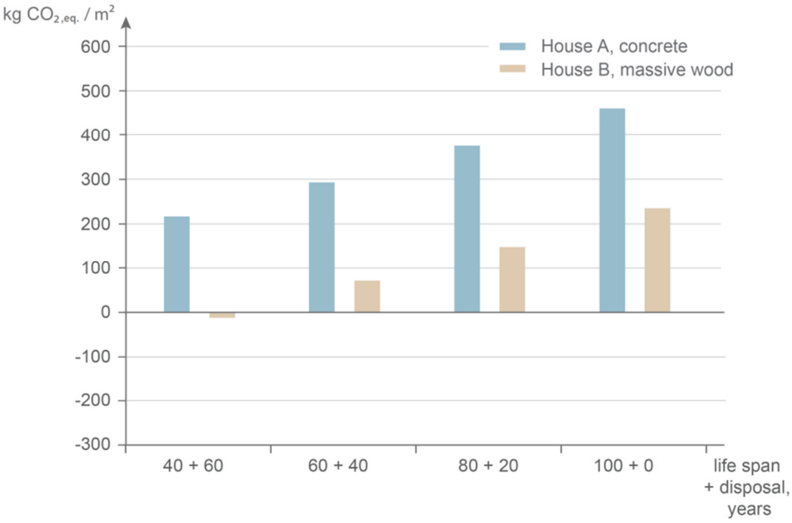


*Figure 29. LCA with varying service and disposal life including wood scrap incineration.*

If the system boundaries are extended to include the forest sequestration cycle, seen in Figure 30, the GWP is negative even for the shortest life spans since the operational heating is under a shorter period but the reforestation still lasts 100 years. To make the life span comparison more justified the last two figures show results with operation time fixed to 100 years where houses with shorter life spans are demolished and rebuilt. The time horizon in Figure 31 is fixed for 100 years and in Figure 32 it is non-limited, which means that time for forest replantation to fully regrow and concrete to fully carbonate is included. Reforestation is set to be 0%, 30% and 60% after 20, 40 and 60 years respectively.

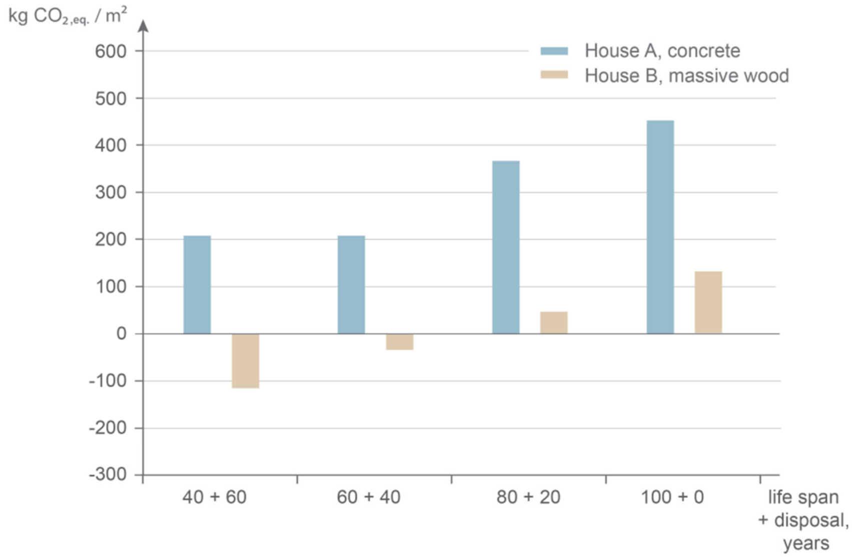


*Figure 30. LCA with varying service and disposal life including biogenic carbon cycle.*

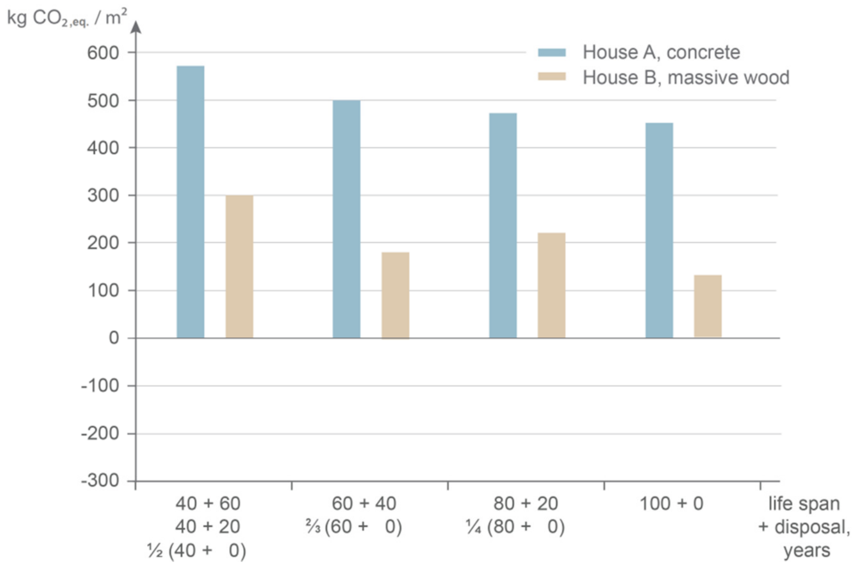


*Figure 31.LCA for 100 years of house rotations including biogenic carbon cycle.*

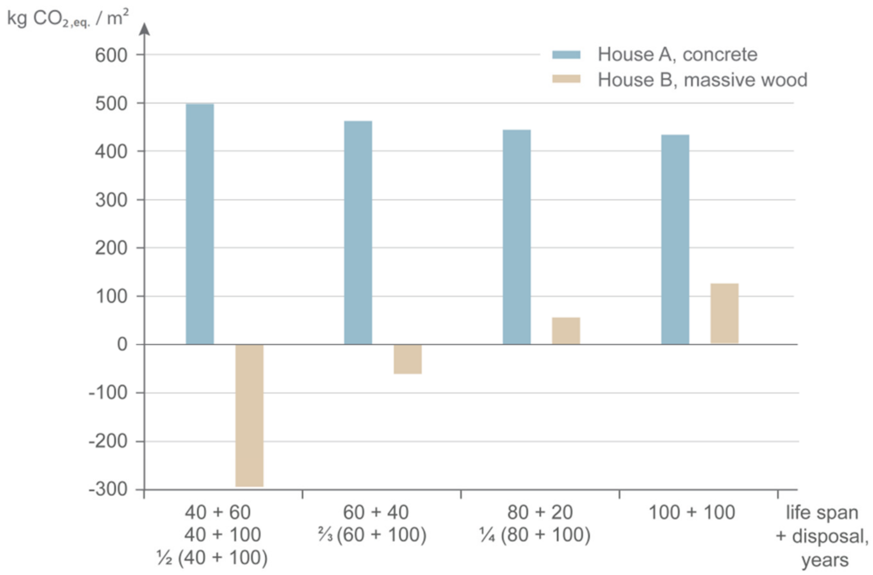


*Figure 32. LCA for 100 years of house rotations but with non-limited disposal time.*

# 6 Interpretation of results

It has been noticed that the system boundaries on the wooden carbon cycle is highly decisive for the LCA results comparing concrete and wooden structures. When limiting the system boundaries to the life cycle of the construction industry (Figure 28), the total GHG emissions for the different structures are close to equal, especially if concrete carbonatation is included. When including the advantages from the wood incineration substituting fossil fuel and carbon sequestration of the reforestation the wood alternative becomes outstandingly better (Figure 29 and Figure 30).The life span of buildings and alternate of time horizon make significant changes on the assessment results. It can be concluded that for a limited time horizon it is favourable to build as long-lasting buildings as possible. But since the wooden carbon cycle is so dominating speaks in order to short-lasting building rotations, since it takes into account every forest rotation associated with each house rotation. That speaks for increasing the forestry, but it shouldn't be interpreted that long-lasting buildings are less preferable. The best would be long-term carbon storage and increased forestry and substitution of fossil fuels. Comparing the results with LCA studies conducted earlier by different authors show that the results are very varying because of different system boundaries.

*Table 4. Housing in concrete and wood frames compared in performed LCA.*

| Authors (Company/University) | Year | Building type | Lifespan (years) | Energy (CED) | Wood (kg $CO_2/m^2$) | Concrete (kg $CO_2/m^2$) | Conc./ Wood |
|---|---|---|---|---|---|---|---|
| O'Connor, Dangerfield (Forintek) | 2004 | Toronto housing | 20 | + 19 % | 732 | 940 | + 28 % |
| Lippke, et. al (CORRIM) | 2004 | Atlanta single-family house | 75 | + 16 % | 107 | 140 | + 31 % |
| Sathre & Gustavsson | 2006 | Wälludden, 4-storey residential | 100 (+bio.) | +27 % | -41 | 22 | ~ |
| Gerilla, Teknomo, Hokao (Saga) | 2007 | Japanese housing | 35 | + 19 % | 490 | 607 | + 24 % |
| Bruzell (Tyréns/Folkhem) | 2012 | Strandparken, 8-storey residential | 100 (+bio.) | - | 320 | 620 | + 94 % |
| Eriksson, Norén & Peñeloza (SP) | 2013 | Wälludden, 4-storey residential | 100 | + 3 % | 669 (frame) | 861 | + 29 % |
| Eriksson, Norén & Peñeloza (SP) | 2013 | Wälludden, 4-storey residential | 100 (+bio.) | + 24 % | 536 (CLT) | 861 | + 61 % |
| Eriksson, Norén & Peñeloza (SP) | 2013 | Wälludden, 4-storey residential | 100 (+dyn.LCA) | + 24 % | 300 (CLT) | 712 | + 137 % |
| *Lundgren (Chalmers)* | *2014* | *Strandparken, 8-storey structure* | *100* | - | *403* | *478* | *+19 %* |
| *Lundgren (Chalmers)* | *2014* | *Strandparken, 8-storey structure* | *100 (+bio.)* | - | *125* | *433* | *+246 %* |

All the authors of the studies above assume in the end of life that the wooden structure is combusted through incineration after service life. The heat produced in the process is a surplus that in LCA usually is allocated to be used earlier in the life cycle, or put aside but still seen as a surplus. As result of the incineration the carbon dioxide stored in the wood is once again released into the air. Through all the studies here mentioned is the wood incineration replacing burning of oil, coal or natural gas. Which fossil fuel is calculated to be replaced make a huge difference in the results.

The difference between biogenic and fossil carbon emissions is that the biogenic carbon could be seen as carbon-neutral-equals-climate-neutral because of the forest carbon balance of photosynthesis and respiration, dependent on deforestation and regeneration. As earlier mentioned the forest volume in Sweden is growing which results in an increasing carbon uptake. Fossil carbon released by burning non-renewable fuels stored in the long-term lithosphere makes a greater impact because of the addition of the carbon to the more sensible *troposphere* (air), *hydrosphere* (water) and *biosphere* (ecosystems). However biogenic carbon can alternatively be seen as equal to fossil carbon in the way it is also carbon dioxide which has the same greenhouse effect. Assume a future scenario in 100 years when energy production is free of fossil fuels and biofuels are still emitting biogenic carbon dioxide. If we find a rational way for landfill or repository disposal we could bind carbon for the long-term. In a short-term perspective we should instead consider reusing or recycling the wooden product or downcycling the material for a purpose with less demand on strength or appearance.

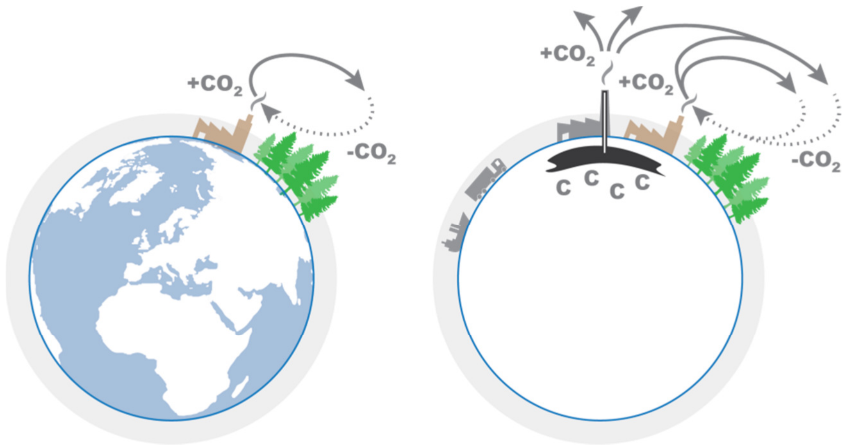


*Figure 33. Biogenic carbon sequestration cycle and amplifying fossil carbon emissions.*

This should be weighed against that long-term carbon storage in wooden buildings which equals absence of carbon dioxide in the atmosphere which decreases the radiative forcing. The results of sequestration comparing with SP are unjustified since the two LCA studies are including different aspects. SP assumes a balance sequestration cycle but use formulas for dynamic LCA to calculated effects of storing carbon in wood for 100 years. The performed LCA in this thesis doesn't calculate the carbon storage effects but assumes 15 % of the reforestation volume never gets incinerated (left in soil, landfill in disposal stage or left in incineration rests) and using the IPCC model in GaBi the total sequestration balance gives a negative GWP (-661,7 kg $CO_{2,eq.}/m^2$ reforestation vs. 558,4 kg $CO_{2,eq.}/m^2$ incineration emission). In the reality both this factors, including that Sweden has an increasing forest volume, should be considered, which speaks even more of the benefit of using wood.

These results are as earlier mentioned not comprehensive as a complete LCA. Other impact categories like land use and resource depletion should be included to get a full view of the environmental impact, but it could give an indication of how to reduce the GHG emission impact of the building sector. Wood is not to be recommended in regions of the world where forest devastation is a problem, but in a country like Sweden which has an increasing carbon volume through forestry there are large advantages for increasing the use of wood in the building industry, especially when there are improved solutions for construction cost, fire resistance and acoustics.

## 6.1 Sensitivity analysis

The results on wood incineration and reforestation obtained with the IPCC model in GaBi including the sequestration cycle differ greatly from the earlier LCA comparison of concrete and wood structures done in 2013 by SP[56]. The part of carbon storage in buildings and sequestration of replanting trees is crucial for final interpretation of the results and thus a sensitivity analysis on wood incineration and reforestation is performed. To bring perspective into the topic of carbon sequestration two reference studies are given as examples of current research on *dynamic LCA,* see chapter 6.1.2.

### 6.1.1 Incineration and reforestation

Approximately 510 tonnes dry wood (430 kg/m³) is used in Strandparken house B , excluding the façade. Approximately 50% of it is stored carbon which with a ratio of carbon to carbon dioxide of 1:3,7 is equivalent to 940 tonnes $CO_{2,eq}$[57]. As mentioned in the extraction chapter for a Nordic spruce ready for harvesting after 90 years only a little bit more than half of the tree is stemwood and a large part of this is lost during manufacturing as pulpwood for paper production or wood chips, scrap rests and sawdust. Since the reforestation is set to equal the amount of harvesting it can be calculated backwards that the American lumber manufacturing data in GaBi assumes of the original harvested forest containing 2640 tonnes $CO_2$ only 35,6% is used in the final structure. Of this 90% is assumed to be collected in disposal and GaBi calculates with an incineration efficiency of 88 % (1 kg wood = 1,6 kg $CO_{2,eq.}$), so finally 750 tonnes is emitted during the end wood incineration. This is half compared with the 1470 tonnes $CO_{2,eq.}$ which is emitted from wood incineration directly from process scrap and within 10 years of the downcycled paper products.

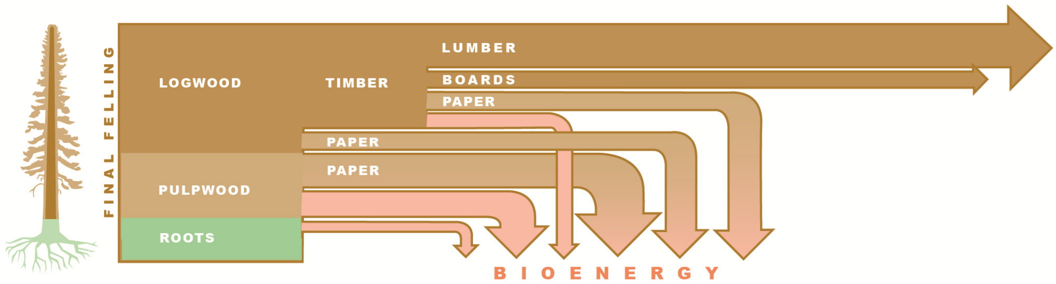


*Figure 34. Distribution of final felling during production line of Swedish wood industry.*

To investigate the accuracy of the GaBi data the results of wood processing losses and carbon storage in reforestation a simulation is done in *CO2FIX 3.2*, using a calculation model from 2009 made by researchers at Wageningen University in Netherlands[58]. In the simulation Nordic spruce (growth and yield tables from Koivisto 1959 and Marklund 1988) is reforested every 90 years where 80 % of the logwood goes to lumber and 20 % to paper together with all the pulpwood. For waste in the lumber production line 16 % is reallocated as boards, 20 % as paper ant 15 % as bioenergy. For paper production 40 % is lost and is reallocated as bioenergy. Thinning of the plantation is done after 40, 60 and 80 years. Of the first and second thinning, 30 % is harvested to 85 % pulpwood and the rest is slash that degrades to soil. For the third thinning 30 % is harvested to 30 % logwood and 60 % pulpwood. And for the final total harvesting 60 % goes to logwood and 30 % to pulpwood.

[56] Eriksson, et al., *Life Cycle Assessment of Different Building Systems*, 2013.
[57] Skogsstyrelsen, *Skogsstatistiska Årsboken*, 2013.
[58] Schelhaas, et al., *CO2FIX V 3.1 - A modelling framework*, 2004.

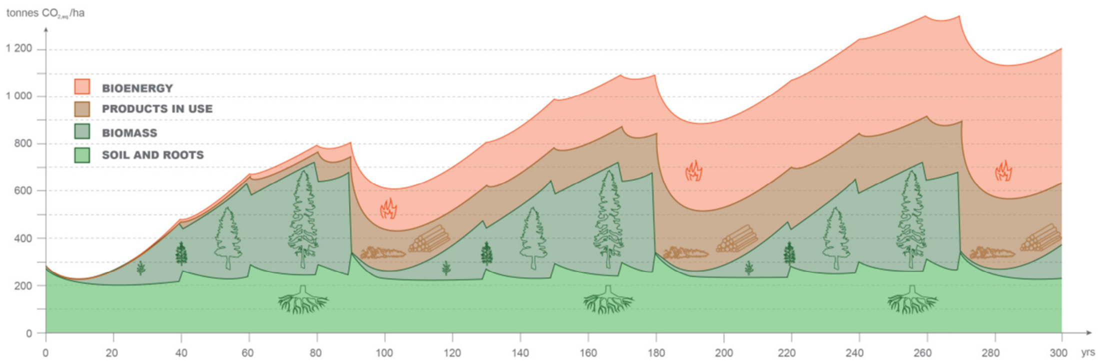


*Figure 35. Simulation with CO2FIX for Nordic spruce with 90 years rotation for 300 years.*

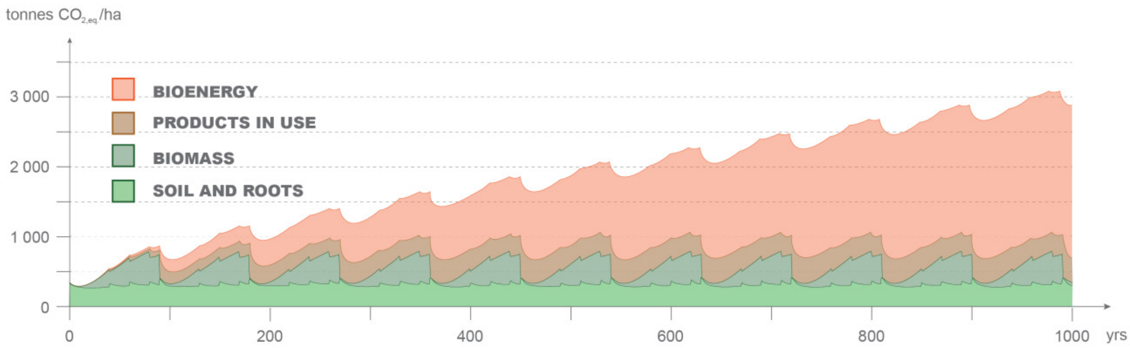


*Figure 36. Simulation with CO2FIX for Nordic spruce with 90 years rotation for 1000 years.*

The simulation shows that the carbon stock of products in use increases the first rotations but then stabilises and no further accumulation takes places. This is because of the short lifetimes of products in the Swedish wood industry. In the simulation 35 % of the lumber last 50 years, 45 % last 10 years and 20 % last only 1 year together with 100 % of the paper. For the logwood then 30 % goes to recycling, 35 % to bioenergy and 35 % to landfill. However, while the biomass stabilise in rotation cycles, the amount of total biomass used for energy keeps on increasing with about 200 tonnes $CO_{2,eq.}$/ha per rotation. Seeing this as a substitution of fossil fuels there are tremendous advantages of a balanced forestry for climate change.

Comparing with the LCA calculations they are made with a time horizon of 100 years and the rotation is 90 years, and during those last 10 years all wood except 35,6 % is assumed incinerated. For CO2Fix based on Swedish industry data this proportion is 42 % (175 tonnes $CO_{2,eq.}$/ha), with a reference soil level of 200 tonnes $CO_{2,eq.}$/ha substituted. The 510 tonnes dry wood in Strandparken house B equals 1440 tonnes of harvested forest which is approximately 5,8 hectares of forest (based on mature Swedish forest average of 222 $m^3$/ha and tree density of 900 kg/$m^3$). That result in a total of -1160 tonnes or -290 kg $CO_{2,eq.}/m^2$ in fossil fuel substitution which is in between the LCA results -252,7 $CO_{2,eq.}/m^2$ by author or -307 $CO_{2,eq.}/m^2$ by SP.

The results in CO2Fix and the ones by SP imply that the fossil fuel substitution using bioenergy could be even larger, hence the LCA results for the carbon sequestration cycle in this case study could be seen conservative, in speaking in the favour of wood.

### 6.1.2 Dynamic LCA

Dynamic LCA, meaning that future predictions is integrated in the LCA calculations, is usually used for future improved energy systems, but could also attend atmospheric content of greenhouse gases. Sequestration through carbon storage could in the long-term cause a decreasing *radiative forcing* of energy in the atmosphere. Researchers at Yale University in Connecticut and Norwegian University in Trondheim have in their research[59] from 2012 compiled and developed the model of calculating the GWP reduction of carbon storage in biomass. By using the Bern Model Impulse Response Function from 2001, adopted by UN's climate panel IPCC, GHG emissions can be weighted equivalent in carbon dioxide. $C_0$ is the magnitude of the impulse emission and $\alpha$ the radiative efficiency of gases.

$$y(t) = \frac{C_0 \int_0^{TH} \alpha_{GHG} \cdot y_{GHG}(t)\, dt}{C_0 \int_0^{TH} \alpha_{CO_2} \cdot y_{CO_2}(t)\, dt} \qquad \text{(Eq. 2)}$$

If carbon dioxide is stored in biomass the biogenic credit $GWP_C$ is substituted from the biogenic $CO_2$ pulse $GWP_{BP}$. By adding the time delay of biogenic $CO_2$ pulse, because of the anthropogenic storage time τ, the actual emissions take place when the biomass is combusted.

$$GWP_{bio} = GWP_{BP} - GWP_C = \frac{C_0 \int_0^{TH} \alpha_{CO_2} \cdot f_{tot}(t)\, dt}{C_0 \int_0^{TH} \alpha_{CO_2} \cdot y(t)\, dt} \qquad \text{(Eq. 3)}$$

, where
$$f_{tot}(t) = \begin{cases} f1(t) = -\int_0^{\tau} g(t')y(t-t')\, dt' \text{ , for } 0 \le t < \tau \\ f2(t) = y(t-\tau) - \int_0^{\tau} g(t')y(t-t')\, dt' \text{ , for } t \ge \tau \end{cases}$$

They used this equation to compare variations of the forest rotation period (1-100 years) and carbon storage, hence the building's life span (20-100 years). In their study they showed that a negative GWP was achieved when the carbon storage time was approximately more or equal to half of the forest rotation time.

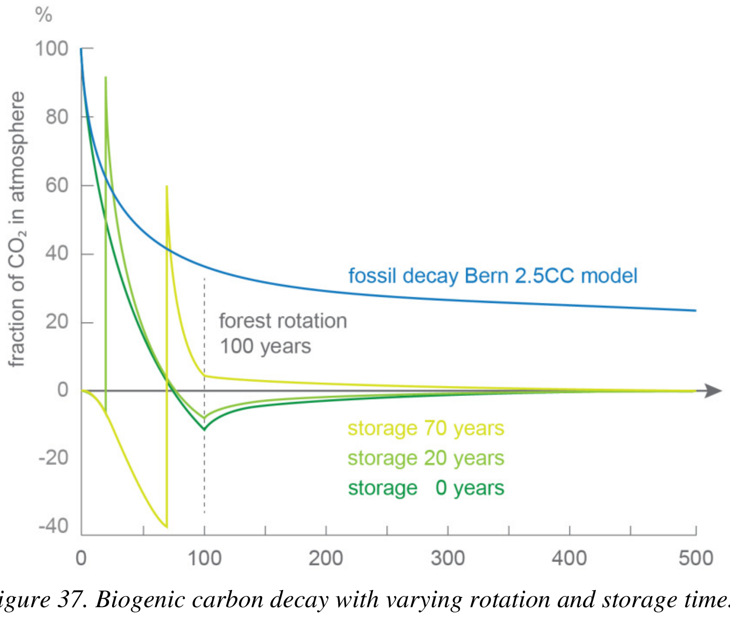


*Figure 37. Biogenic carbon decay with varying rotation and storage time. Redrawn after Guest, et. al (2012).*

[59] Guest, et. al, *Global Warming Potential of Carbon Dioxide Emissions from Biomass...*, 2012.

Researchers at École Polytechnique de Montréal[60] in a following study applied this type of dynamic LCA model of a wooden chair of 5 kg. The chair has a service life of 2x50 years and meanwhile the reforestation rotation is set to 70 years. By varying between four end-of-life scenarios for the two chairs it could be shown that for a short-term perspective refurbishing the first chair to last 50 years more and then landfill it gave the most negative cumulative radiative forcing in the atmosphere, thus negative GWP. While in a long-term perspective it was better to incinerate the two chairs with energy recovery. When landfilling both of them, even though some methane is emitted from decaying wood waste, the prolonged carbon storage kept out from the atmosphere gave the long-term most negative GWP.

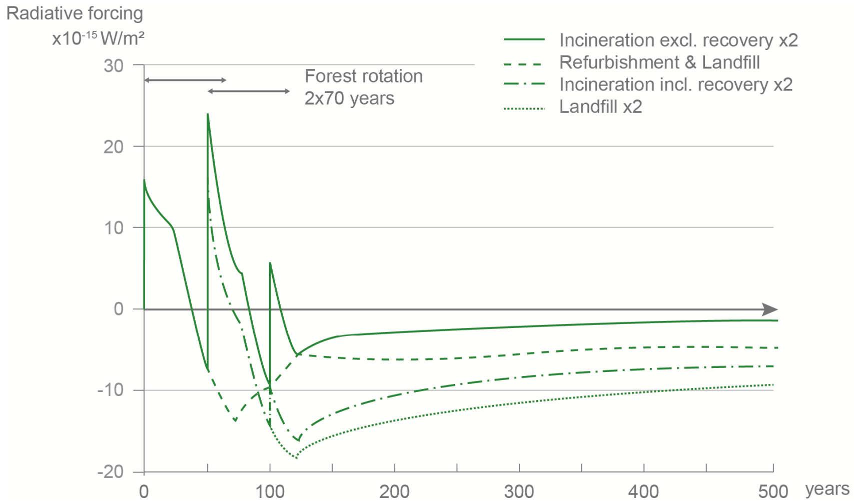


*Figure 38. Instaneous radiative forcing by life-cycle of two wooden chairs. Redrawn Levasseur, et. al (2013).*

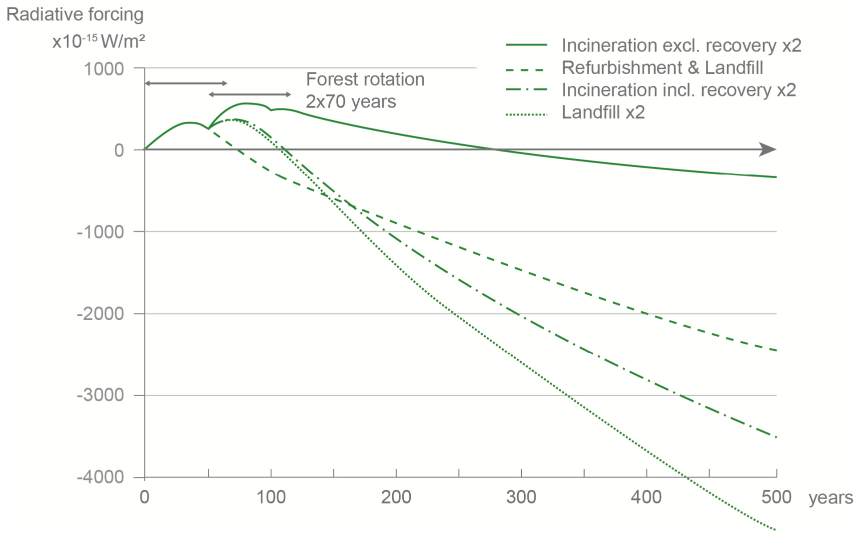


*Figure 39. Cumulative radiative forcing by life-cycle of two wooden chairs. Redrawn Levasseur, et. al (2013).*

For life expectancy of wooden buildings dynamic LCA should be considered in terms of the impact of storing carbon long-term away from the atmosphere. Both studies presented here imply that the time horizon is critical for the results. How dynamic LCA would affect the LCA case study results have not been calculated, but according to the study by SP, the change in results including carbon storage in the housing structure using dynamic LCA are substantial (see Table 4).

[60] Levasseur, et al., *Biogenic Carbon and Temporary Storage Addressed with Dynamic LCA*, 2013.
[61] Eriksson, et al., *Life Cycle Assessment of Different Building Systems*, 2013.

# 7 Conclusions

In most cases the building life span is not dependent on the structure and no consensus can be found in difference in lifespan of wood or concrete building. Instead the climate impact should be referred to the emissions and energy use in the life cycle processes. For a multi-residential building a concrete structure becomes around three times heavier than a wood structure, hence the weight of cement and wood is roughly the same. Using wood in buildings can work as long-term carbon storage, decreasing the atmospheric content of carbon dioxide. After usage the wood today is incinerated with energy recovery used as substitution to fossil fuels. That may though not be the case in hundred years when the wood has served its purpose. When energy supply by fossil fuel possibly has decreased, and wood incineration instead should be compared to renewable energy sources, the best alternatives for end use of wood instead could be landfill or refurbish into other non-structural purposes.

When limiting the system boundaries of the LCA of wooden and concrete structures to only the building industry the GHG emissions are more equal. The cement calcination during manufacturing has a huge impact on increasing the GHG emissions, but in this case study up to half of the emitted carbon dioxide in the concrete will be recaptured in the long term. Through cement carbonatation concrete has a chance to rebind up to half of its emitted carbon dioxide during production. But since concrete carbonatation is seen as a problem in reinforced concrete the emphasis has to lay on the industry to let landfilled crushed concrete aggregate carbonate after service life. This could though be a problem since there is less economical company profit for this compared with landfilling.

For the Swedish building sector to be able to decrease its GHG emissions, the awareness need to increase of life-cycle assessment and climate impact by material choice need to increase. By increasing the proportion of newly constructed multi-residential buildings in wood, the building industry which demands both a combination of governmental regulation and willingness of change in the industry. Regardless if the significantly, according to the lowered energy demands the following decades, the life span of the existing building stock is growing very fast and energy-efficient demands on renovation is crucial. Important here is that we maintain the buildings to last longer, especially through replacement of component vital for the service life, e.g. façade, plumbing and building services. And in the same way this has to be done in an energy-efficiency improving way, but still subsidized enough to let the residents afford to continue living there.

The performed study should be seen as a screening LCA only regarding GHG emissions of house structures. For total environmental impact all standardized impact categories should have been weighted together. Much of the gathered data are generalized and accuracy of impact results in the specific case study could therefore be questioned. Other potential future development of this thesis if more time existed could have included examine the influence of dynamic LCA in results. This study has, from an academic perspective through immersed understanding of the LCA methodology and the life-cycles of building materials, created a basis for the author in working for more sustainable architecture.

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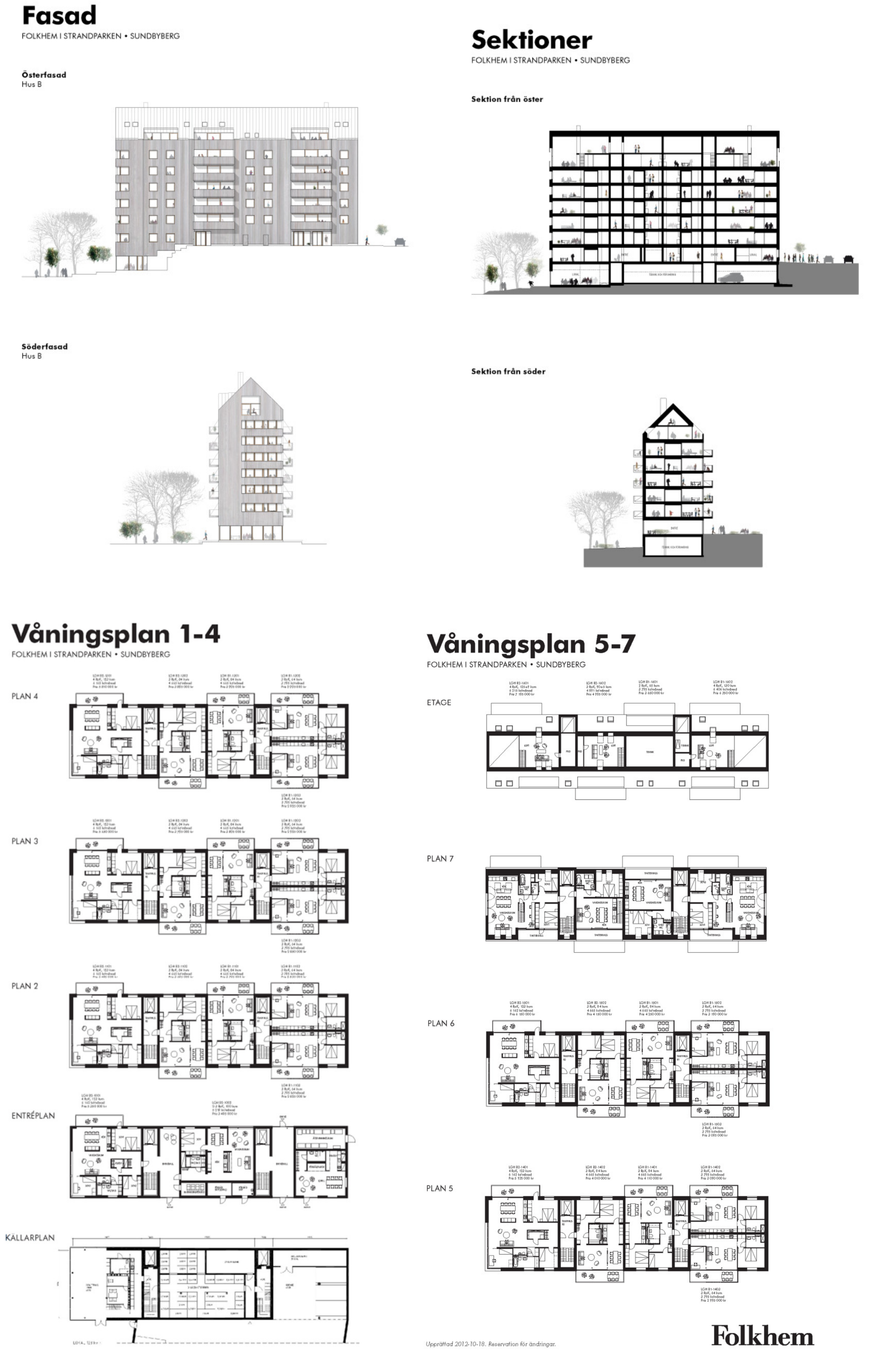
*Photos are taken and charts are illustrated by the author if not stated otherwise.*

# Appendix

# Appendix A: Architectural drawings of house B




*Architectural drawings distributed by Folkhem.*

# Appendix B: Inventory calculations for case study alternatives

## Strandparken, House B

8 storey massive wood frame, Atemp = 3981 m²

| | m² | mm (rel.) | m³ | kg/m³ | kg | λ | U-value |
|---|---|---|---|---|---|---|---|
| **EXTERIOR ROOF** | **762** | | | | **77935,9** | | |
| *Cedar chips, lath, underlay felt* | | | | | | | |
| Plywood | | 12 | 9 | 430 | 3931,9 | | |
| Timber Lath 45x45 cc765 | | 3 | 2 | 430 | 867,3 | | |
| *Wind barrier* | | | | | | | |
| Glue Laminated Timber 495x45 cc765 | | 29 | 22 | 430 | 9540,7 | | |
| Rock wool 3*170+80 | | 590 | 450 | 30 | 13487,4 | | |
| *PE Foil* | | | | | | | |
| Glue Laminated Timber | | 95 | 72 | 430 | 31127,7 | | |
| Timber Lath 28x70 cc300 | | 7 | 5 | 430 | 2140,7 | | |
| Gypsum Board | | 26 | 20 | 850 | 16840,2 | | |
| | | | | | | | |
| **EXTERIOR WALL YV-16-01** | **1552** | | | | **127416,0** | λ | U-value |
| *Cedar chip, lath, studs, wind barrier* | | | | | | **W/m²K** | **W/mK** |
| Plywood 12x70 cc600 | | 1 | 2 | 430 | 934,3 | 0,14 | 0,160 |
| Timber studs 2*70x45 cc600 | | 17 | 26 | 430 | 11367,4 | 0,14 | |
| Rock wool 3*70 | | 193 | 299 | 30 | 8984,5 | 0,04 | |
| *PE foil* | | | | | | | |
| Glue Laminated Timber | | 120 | 186 | 430 | 80083,2 | 0,14 | |
| Gypsum Board | | 15 | 23 | 850 | 19788,0 | 0,25 | |
| Tension Steel Rod 9* ø20 | 0,01 | 20000 | 0,23 | 7800 | 1763,4 | | |
| Steel Pillar (VKR) 100x100 | 0,01 | 20000 | 0,10 | 7800 | 780,0 | | |
| Glulam pillar 15*240x120 | 0,432 | 20000 | 8,64 | 430 | 3715,2 | | |
| | | | | | | | |
| Interior Wall IV-03-03 (Elevator Shaft) | 450 | | | | | | |
| Gypsum Board | | 15 | 6,8 | | | | |
| Glue Laminated Timber | | 120 | 54,0 | | | | |
| Tension Steel Rod 6* ø20 | 0,01 | 20000 | 0,15 | | | | |
| | | | | | | | |
| Interior Wall IV-03-04 | 1001 | | | | | | |
| Gypsum Board 2*15 | | 30 | 30 | | | | |
| Glue Laminated Timber | | 170 | 170 | | | | |
| | | | | | | | |
| Apartment Separating Wall LS-07-04 | 2721 | | | | | | |
| Gypsum Board 2*15 | | 30 | 82 | | | | |
| Construction Plywood | | 12 | 33 | | | | |
| Timber studs 45x120 cc600 | | 9 | 24 | | | | |
| Rock wool 120 | | 111 | 302 | | | | |
| Tension Steel Rod 36* ø20 | 0,05 | 20000 | 0,90 | | | | |
| | | | | | | | |
| Interior Wall IV-03-02 | 310 | | | | | | |
| Gypsum Board 2*15 | | 30 | 9 | | | | |
| Glue Laminated Timber | | 120 | 37 | | | | |
| | | | | | | | |
| **TOTAL INTERIOR WALLS** | **4482** | | | | **262803,5** | | |
| Gypsum Board | | | 128 | 850 | 108553,5 | | |
| Glue Laminated Timber | | | 261 | 430 | 112389,1 | | |
| Timber Spruce | | | 24 | 430 | 10530,3 | | |
| Plywood | | | 33 | 430 | 14040,4 | | |
| Rock Wool | | | 302 | 30 | 9060,9 | | |
| Tension Steel Rod 42* ø20 | | | 1 | 7800 | 8229,3 | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Slab MBK-03-02 (Flange beams) | 789 | | | | | | | |
| Glue Laminated Timber | | 70 | 55 | | | | | |
| GL beams w220x45, f56x180 cc 400 | | 109 | 86 | | | | | |
| Timber Studs 220x45 cc600 | | 17 | 13 | | | | | |
| Rock wool 170+70 | | 216 | 170 | | | | | |
| Lath 28x70 cc300 | | 7 | 5 | | | | | |
| Gypsum Board 2*13 | | 26 | 21 | | | | | |
| | | | | | | | | |
| Slab MB-02-01 (Solid slab) | 1723 | | | | | | | |
| Glue Laminated Timber | | 145 | 250 | | | | | |
| Timber Studs 45x220 cc600 | | 23 | 40 | | | | | |
| Rock wool 70+170 | | 227 | 392 | | | | | |
| Lath 28x70 cc300 | | 7 | 11 | | | | | |
| Gypsum Board 2*13 | | 26 | 45 | | | | | |
| | | | | | | | | |
| Slab Stairwell | 241 | | | | | | | |
| Glue Laminated Timber | | 120 | 29 | | | | | |
| | | | | | | | | |
| Slab MB-03-04 (Floor 7-8) + balconies | 219+304 | | | | | | | |
| Glue Laminated Timber | | 170 | 89 | | | | | |
| | | | | | | | | |
| **SLABS, STAIRWELL & BALCONIES** | **3276** | | | | **322177,8** | | | |
| Gypsum Board | | | 89 | 850 | 75303,2 | | | |
| Glue Laminated Timber | | | 454 | 430 | 195059,4 | | | |
| Timber Spruce | | | 79 | 430 | 34030,5 | | | |
| Plywood | | | 2 | 430 | 934,3 | | | |
| Rock Wool | | | 562 | 30 | 16850,4 | | | |
| *Flooring* | | | | | | | | |
| | | | | | | | | |
| **BASEMENT & FOUNDATION** | | | | | **792844,5** | | | |
| Hollow Concrete Slab ( Floor 1) | 490 | 200 | 98 | 1000 | 98000,0 | | | |
| Concrete Walls (Floor -1) | 594 | 200 | 118,8 | 2400 | 285120,0 | | | |
| Concrete Slab | 535 | 300 | 160,5 | 2400 | 385200,0 | | | |
| Reinforcing bars | | | | 65 | 24524,5 | | | |
| *Extruded Polystyrene* | *535* | *300* | *160,5* | *40* | | | | |
| *Macadam* | *600* | *200* | *120* | *1600* | | | | |
| | | | | | | | | |
| **TRANSPORT** | | | **tonnes** | **km** | **tkm** | | | |
| Total transport (calculated Tyréns) | | | | | 838000 | | | |
| Modules Bygdsiljum-Sundbyberg | | | 790 | 705 | 557185 | | | |
| Rest of extraction transport | | | | | 280815 | | | |
| | | | | | | | | |
| **CONSTRUCTION TENT** | **m²** | **kg/m²** | **kg** | **use** | **kg/use** | | | |
| Gibson Aluminum truss bays | 1000 | 10 | 10000 | 20 | 500,0 | | | |
| Gibson Steel towers | 1000 | 30 | 30000 | 20 | 1500,0 | | | |
| PVC fabric | 1800 | 0,6 | 1080 | 10 | 108,0 | | | |
| | | | | | **2108,0** | | | |
| | | | | | | | | |
| | | | | | **kg** | **disposal waste** | | |
| **TOTAL** | | | | | **1583177,7** | | **kg** | |
| Glue laminated timber | | | | | 431915,3 | 90% | 388723,8 | Incin. |
| Plywood | | | | | 19840,9 | 90% | 17856,8 | Incin. |
| Timber Spruce | | | | | 58936,2 | 90% | 53042,6 | incin. |
| Rock Wool | | | | | 48383,3 | 0% | | |
| Gypsum board | | | | | 220484,9 | 25% | 55121,2 | Recyc. |
| Concrete | | | | | 768320,0 | 3% | 23049,6 | Recyc. |
| Steel rebar | | | | | 35297,2 | 70% | 24708,1 | Recyc. |

| MAINTENANCE 40/60/80/100 yrs | | Gypsum Years | Life span Building Years | Change | kg (old) | kg (new) | disposal waste | kg | |
|---|---|---|---|---|---|---|---|---|---|
| 1) | Gypsum board new | 40-80 | 40 | 0% | 202484,9 | 0,0 | 25% | 0,0 | Recyc. |
| 2) | Gypsum board new | 40-80 | 60 | 50% | 202484,9 | 110242,5 | 25% | 27560,6 | Recyc. |
| 3) | Gypsum board new | 40-80 | 80 | 100% | 202484,9 | 220484,9 | 25% | 55121,2 | Recyc. |
| 4) | Gypsum board new | 40-80 | 100 | 125% | 202484,9 | 253106,1 | 25% | 63276,5 | Recyc. |

| | | Exposed | | CEM II 1,05 | | | Corr. factor | | |
|---|---|---|---|---|---|---|---|---|---|
| **CARBONATATION 40+60 yrs** | | **m²** | **Years** | **C. Rate** | **% vol.** | **kg CO2** | **Vol.** | **Max** | **GHG** |
| | Operation: Indoor surfaces | 2109 | 40 | 4,41 | 15,6% | 8909,0 | 1 | 75% | |
| | Operation: Buried surfaces | 1129 | 40 | 1,05 | 2,0% | 1135,5 | 1 | 75% | |
| | | | | | **17,6%** | **10044,5** | | | 11% |
| 63% | Disposal: RCA to road filling | 93264 | 60 | 1,05 | 36,2% | 20672,4 | 0,33 | 75% | |
| 34% | Disposal: Landfill & RCA to paving | 50333 | 60 | 1,58 | 19,5% | 11156,5 | 0,33 | 75% | |
| 3% | Disposal: RCA to new concrete | 76 | 60 | 1,58 | 0,0% | 5,1 | 1 | 75% | |
| | | | | | **55,7%** | **31834,1** | | | 36% |
| | | | | | *73,3%* | | | | |

| | | Exposed | | CEM II 1,05 | | | Corr. factor | | |
|---|---|---|---|---|---|---|---|---|---|
| **CARBONATATION 60 + 40 yrs** | | **m²** | **Years** | **C. Rate** | **% vol.** | **kg CO2** | **Vol.** | **Max** | **GHG** |
| | Operation: Indoor surfaces | 2109 | 60 | 4,41 | 19,1% | 10911,2 | 1 | 75% | |
| | Operation: Buried surfaces | 1129 | 60 | 1,05 | 2,4% | 1390,7 | 1 | 75% | |
| | | | | | **21,5%** | **12301,9** | | | 14% |
| 63% | Disposal: RCA to road filling | 93264 | 40 | 1,05 | 33,7% | 19250,2 | 0,33 | 75% | |
| 34% | Disposal: Landfill & RCA to paving | 50333 | 40 | 1,58 | 18,2% | 10389,0 | 0,33 | 75% | |
| 3% | Disposal: RCA to new concrete | 76 | 40 | 1,58 | 0,01% | 4,4 | 1 | 75% | |
| | | | | | **51,9%** | **29643,6** | | | 33% |
| | | | | | *73,4%* | | | | |

| | | Exposed | | CEM II 1,05 | | | Corr. factor | | |
|---|---|---|---|---|---|---|---|---|---|
| **CARBONATATION 80 + 20 yrs** | | **m²** | **Years** | **C. Rate** | **% vol.** | **kg CO2** | **Vol.** | **Max** | **GHG** |
| | Operation: Indoor surfaces | 2109 | 80 | 4,41 | 22,0% | 12599,2 | 1 | 75% | |
| | Operation: Buried surfaces | 1129 | 80 | 1,05 | 2,8% | 1605,9 | 1 | 75% | |
| | | | | | **24,9%** | **14205,1** | | | 16% |
| 63% | Disposal: RCA to road filling | 93264 | 20 | 1,05 | 31,6% | 18051,3 | 0,33 | 75% | |
| 34% | Disposal: Landfill & RCA to paving | 50333 | 20 | 1,58 | 14,0% | 8017,5 | 0,33 | 75% | |
| 3% | Disposal: RCA to new concrete | 76 | 20 | 1,58 | 0,0% | 3,2 | 1 | 75% | |
| | | | | | **45,6%** | **26072,0** | | | 29% |
| | | | | | *70,5%* | | | | |

| | | Exposed | | CEM II 1,05 | | | Corr. factor | | |
|---|---|---|---|---|---|---|---|---|---|
| **CARBONATATION 100 + 0 yrs** | | **m²** | **Years** | **C. Rate** | **% vol.** | **kg CO2** | **Vol.** | **Max** | **GHG** |
| | Operation: Indoor surfaces | 2109 | 100 | 4,41 | 24,7% | 14086,3 | 1 | 75% | |
| | Operation: Buried surfaces | 1129 | 100 | 1,05 | 3,1% | 1795,4 | 1 | 75% | |
| | | | | | **27,8%** | **15881,7** | | | 18% |
| 63% | Disposal: RCA to road filling | 93264 | 0 | 1,05 | 0,0% | 0,0 | 0,33 | 75% | |
| 34% | Disposal: Landfill & RCA to paving | 50333 | 0 | 1,58 | 0,0% | 0,0 | 0,33 | 75% | |
| 3% | Disposal: RCA to new concrete | 76 | 0 | 1,58 | 0,00% | 0,0 | 1 | 75% | |
| | | | | | **0,0%** | **0,0** | | | 0% |
| | | | | | *27,8%* | | | | |

## Strandparken, House A

8 storey prefab concrete frame, Atemp = 3981 m²

| | m² | mm (rel.) | m³ | kg/m³ | kg | λ | U-value |
|---|---|---|---|---|---|---|---|
| **EXTERIOR ROOF** | **762** | | | | **77936,0** | | |
| *Tin roof, T&G sheets* | | | | | | | |
| Plywood | | 12 | 9 | 430 | 3931,9 | | |
| Timber Lath 45x45 cc765 | | 3 | 2 | 430 | 867,3 | | |
| Glue Laminated Timber 495x45 cc765 | | 29 | 22 | 430 | 9540,7 | | |
| Rock wool 3*170+80 | | 590 | 450 | 30 | 13487,4 | | |
| Glue Laminated Timber | | 95 | 72 | 430 | 31127,7 | | |
| Timber Lath 28x70 cc300 | | 7 | 5 | 430 | 2140,7 | | |
| Gypsum Board | | 26 | 20 | 850 | 16840,2 | | |
| | | | | | | | |
| **EXTERIOR WALL** | **1552** | | | | **826558,0** | λ | U-value |
| *Cement Render* | | | | | | **W/m²K** | **W/mK** |
| SPU insulation | | 143 | 222 | 32 | 7102,0 | 0,023 | 0,160 |
| Prefab concrete | | 80 | 124 | 2400 | 297984,0 | 1,70 | |
| In-situ concrete | | 120 | 186 | 2400 | 446976,0 | | |
| Steel rebar truss & grids | | | | 240 | 74496,0 | | |
| | | | | | | | |
| **INTERIOR WALLS** | **2185** | | | | **1117910,4** | | |
| Prefab concrete | | 80 | 175 | 2400 | 419520,0 | | |
| In-situ concrete | | 120 | 262 | 2400 | 629280,0 | | |
| Steel rebar truss & grids | | | | 240 | 69110,4 | | |
| | | | | | | | |
| **SLABS, STAIRWELL & BALCONIES** | **3276** | | | | **1005000,0** | | |
| Prefab concrete | | 50 | 164 | 2400 | 393120,0 | | |
| In-situ concrete | | 150 | 233 | 2400 | 558720,0 | | |
| Steel rebar truss & grids | | | | 200 | 53160,0 | | |
| | | | | | | | |
| **BASEMENT & FOUNDATION** | | | | | **947759,7** | | |
| Prefab concrete slab (Floor 1) | 490 | 50 | 25 | 2400 | 58800,0 | | |
| In-situ concrete slab | | 150 | 74 | 2400 | 176400,0 | | |
| Steel rebar truss & grids | | | | 200 | 14700,0 | | |
| | | | | | | | |
| Prefab concrete walls (Floor -1) | 594 | 80 | 48 | 2400 | 114048,0 | | |
| In-situ concrete walls | | 120 | 71,28 | 2400 | 171072,0 | | |
| Steel rebar truss & grids | | | | 240 | 17107,2 | | |
| | | | | | | | |
| In-situ concrete Foundation | 535 | 300 | 160,5 | 2400 | 385200,0 | | |
| Reinforcing bars | | | | 65 | 10432,5 | | |
| *Extruded Polystyrene* | *535* | *300* | *160,5* | *40* | | | |
| *Macadam* | *600* | *200* | *120* | *1600* | | | |

| TRANSPORT | tonnes | km | tkm |
|---|---|---|---|
| Töcksfors-Sundbyberg (Prefab) | 1512 | 421 | 636571 |

| | kg | disposal waste | | |
|---|---|---|---|---|
| **TOTAL** | **3975164,0** | | **kg** | |
| Plywood | 3931,9 | 90% | 3538,7 | Incin. |
| Timber Spruce | 3008,0 | 90% | 2707,2 | Incin. |
| Glue laminated timber | 40668,4 | 90% | 36601,5 | Incin. |
| Rock Wool | 13487,4 | 0% | | |
| Polyurethane | 7102,0 | 0% | | |
| Gypsum board | 16840,2 | 25% | 1775,5 | recyc. |
| Concrete | 3651120,0 | 3% | 505,2 | recyc. |
| Steel rebar | 239006,1 | 70% | 167304,3 | recyc. |

| | | Exposed | | CEM II | 1,05 | | Corr. factor | | |
|---|---|---|---|---|---|---|---|---|---|
| **CARBONATATION 40 + 60 years** | | **m²** | **yrs** | **C. Rate** | **% vol.** | **kg CO2** | **Vol.** | **Max carb** | **GHG** |
| | Operation: Ex. surfaces (covered) | 2160 | 40 | 3,15 | 2,8% | 7681,3 | 1 | 75% | |
| | Operation: Int. surfaces (painted) | 13975 | 40 | 4,41 | 25,6% | 69575,9 | 1 | 75% | |
| | Operation: Buried surfaces | 1129 | 40 | 1,05 | 0,5% | 1338,3 | 1 | 75% | |
| | | | | | **28,9%** | **78595,4** | | | 18,5% |
| 63% | Disposal: RCA to road filling | 309340 | 60 | 1,05 | 24,4% | 66343,8 | 0,33 | 75% | |
| 34% | Disposal: Landfill & RCA to paving | 166945 | 60 | 1,58 | 10,7% | 28984,7 | 0,33 | 75% | |
| 3% | Disposal: RCA to new concrete | 14730 | 60 | 1,05 | 0,2% | 455,9 | 1 | 75% | |
| | | | | | **35,3%** | **95784,4** | | | 22,5% |
| | | | | | 64,2% | | | | **40,9%** |

| | | Exposed | | CEM II | 1,05 | | Corr. factor | | |
|---|---|---|---|---|---|---|---|---|---|
| **CARBONATATION 60 + 40 years** | | **m²** | **yrs** | **C. Rate** | **% vol.** | **kg CO2** | **Vol.** | **Max carb** | **GHG** |
| | Operation: Ex. surfaces (covered) | 2160 | 60 | 3,15 | 3,5% | 9407,6 | 1 | 75% | |
| | Operation: Int. surfaces (painted) | 13975 | 60 | 4,41 | 31,4% | 85212,7 | 1 | 75% | |
| | Operation: Buried surfaces | 1129 | 60 | 1,05 | 0,6% | 1639,1 | 1 | 75% | |
| | | | | | **35,4%** | **96259,3** | | | 22,6% |
| 63% | Disposal: RCA to road filling | 309340 | 40 | 1,05 | 18,1% | 49210,6 | 0,33 | 75% | |
| 34% | Disposal: Landfill & RCA to paving | 166945 | 40 | 1,58 | 7,9% | 21499,4 | 0,33 | 75% | |
| 3% | Disposal: RCA to new concrete | 14730 | 40 | 1,05 | 0,1% | 338,1 | 1 | 75% | |
| | | | | | **26,2%** | **71048,2** | | | 16,7% |
| | | | | | **61,6%** | | | | **39,3%** |

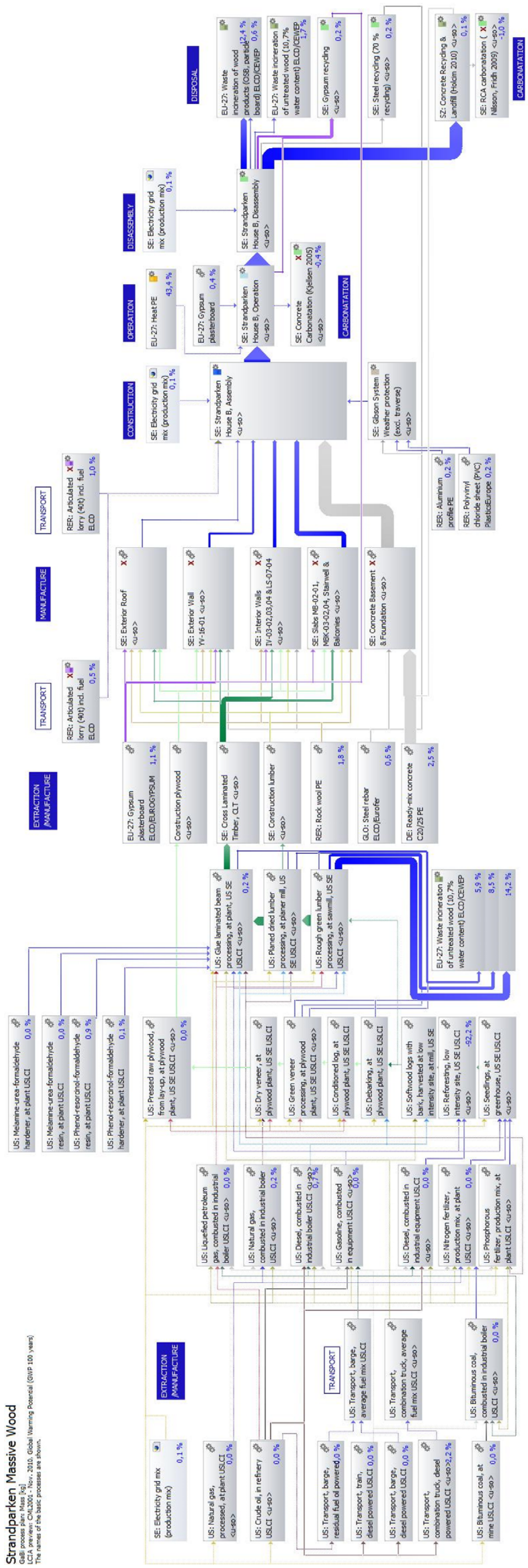
| | | Exposed | | CEM II | 1,05 | | Corr. factor | | |
|---|---|---|---|---|---|---|---|---|---|
| **CARBONATATION 80 + 20 years** | | **m²** | **yrs** | **C. Rate** | **% vol.** | **kg CO2** | **Vol.** | **Max carb** | **GHG** |
| | Operation: Ex. surfaces (covered) | 2160 | 80 | 3,15 | 4,0% | 10862,9 | 1 | 75% | |
| | Operation: Int. surfaces (painted) | 13975 | 80 | 4,41 | 36,2% | 98395,1 | 1 | 75% | |
| | Operation: Buried surfaces | 1129 | 80 | 1,05 | 0,7% | 1892,6 | 1 | 75% | |
| | | | | | **40,9%** | **111150,7** | | | 26,1% |
| 63% | Disposal: RCA to road filling | 309340 | 20 | 1,05 | 11,7% | 31841,1 | 0,33 | 75% | |
| 34% | Disposal: Landfill & RCA to paving | 166945 | 20 | 1,58 | 5,1% | 13910,9 | 0,33 | 75% | |
| 3% | Disposal: RCA to new concrete | 14730 | 20 | 1,05 | 0,1% | 218,8 | 1 | 75% | |
| | | | | | **16,9%** | **45970,8** | | | 10,8% |
| | | | | | 57,9% | | | | **36,9%** |

| | | Exposed | | CEM II | 1,05 | | Corr. factor | | |
|---|---|---|---|---|---|---|---|---|---|
| **CARBONATATION 100 + 0 years** | | **m²** | **yrs** | **C. Rate** | **% vol.** | **kg CO2** | **Vol.** | **Max carb** | **GHG** |
| | Operation: Ex. surfaces (covered) | 2160 | 100 | 3,15 | 4,5% | 12145,1 | 1 | 75% | |
| | Operation: Int. surfaces (painted) | 13975 | 100 | 4,41 | 40,5% | 110009,1 | 1 | 75% | |
| | Operation: Buried surfaces | 1129 | 100 | 1,05 | 0,8% | 2116,0 | 1 | 75% | |
| | | | | | **45,8%** | **124270,3** | | | 29,2% |
| 63% | Disposal: RCA to road filling | 309340 | | 1,05 | 0,0% | 0,0 | 0,33 | 75% | |
| 34% | Disposal: Landfill & RCA to paving | 166945 | | 1,58 | 0,0% | 0,0 | 0,33 | 75% | |
| 3% | Disposal: RCA to new concrete | 14730 | | 1,05 | 0,0% | 0,0 | 1 | 75% | |
| | | | | | **0,0%** | **0,0** | | | 0,0% |
| | | | | | 45,8% | | | | **29,2%** |

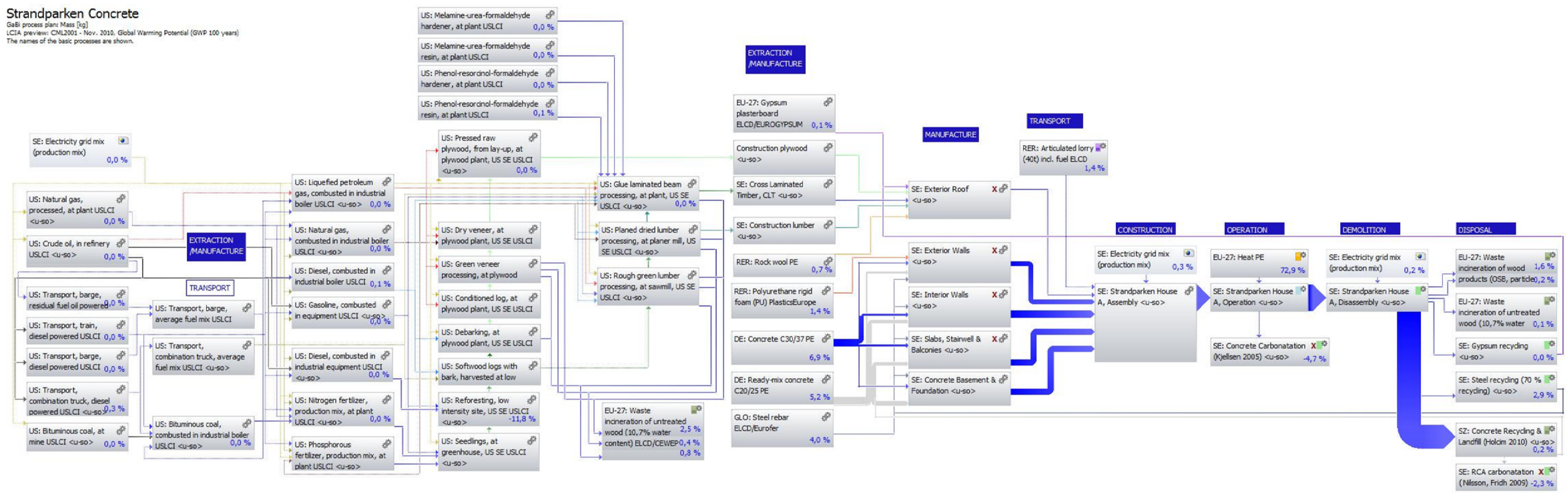
| **C30/37 CEM II** | **concrete** | | **1 t cem** | **1 t conc.** | **1 m³ conc.** | |
|---|---|---|---|---|---|---|
| | **kg/m³** | **%** | **kg CO2** | **%** | **kg CO2** | **kg CO2** |
| concrete, total | 2400 | 100% | 800 | 100% | 117 | 280 |
| cement, total | 350 | 15% | 740 | 93% | 108 | 259 |
| calcination only | | | 510 | 64% | 74 | 179 |

Source: Kjellsen et. al 2005, coherent w. GaBi 2013

# Appendix C: Life Cycle Inventory flow models



*LCI Model of House B (MASSIVE WOOD) made in GaBi LCA Software. Flow thickness showing mass distribution.*




*LCI Model of House A (CONCRETE) made in GaBi LCA Software. Flow thickness showing mass distribution.*

# Appendix D: Results from impact assessment

## CO2 Balance House A

kg $CO_2$,eq./m²  AREA 3981 m²

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **MANUFACTURE** | | **CONSTRUCTION** | | **OPERATION 40 yrs** | | **DISPOSAL 60 yrs** | | **EXT. BOUNDARIES** | | **NON-LIMITED CARBONATATION** | | | | |
| **Gypsum** | 0,5 | **Assembling** | 2,1 | **Heating** | 155,7 | **Disassembly** | 1,1 | Wood incin. Rest | -15,5 | **Max carb.** | **kg conc.** | **$CO_2$/conc.** | **kg $CO_2$** | **kg $CO_2$,eq./m²** |
| **Wood** | 2,6 | **Transport** | 7,9 | **Carbonation** | -19,7 | **Wood incin.** | -8,8 | **Reforestation** | -62,2 | 47,9% | 3651120 | -11,7% | -204406 | *-51,3* |
| **Rock wool** | 3,7 | | | | | **Gypsum** | 0,1 | Incin. Emissi. Rest | 33,2 | | | | | |
| **Polyurethane** | 7,4 | | | | | **Steel** | 16,9 | Incin. Emiss. House | 19,3 | | | | | |
| **Concrete** | 63,7 | | | | | **Concrete** | 1,6 | | | **TOTAL** | | | | |
| **Steel** | 21,1 | | | | | **Carbonation** | -24,1 | | | **incl.:** | | | **OPERATION 100 yrs** | |
| | | | | | | | | | | **Heating** | **Sequest.** | **Substit.** | **Limited** | **Non-limited** |
| | *99,0* | | *10,0* | | *136,0* | | *-13,3* | | *-24,8* | *231,7* | *216,6* | *206,9* | *573,3* | *498,5* |
| | | | | **OPERATION 60 yrs** | | **DISPOSAL 40 yrs** | | | | | | | | |
| | | | | **Heating** | 233,6 | " | " | | | | | | | |
| | | | | **Carbonation** | -24,2 | **Carbonation** | -17,8 | | | | | | | |
| | | | | | *209,4* | | *-7,1* | | | 311,3 | *296,2* | *286,6* | *500,4* | *462,1* |
| | | | | **OPERATION 80 yrs** | | **DISPOSAL 20 yrs** | | | | | | | | |
| | | | | **Heating** | 311,5 | " | " | | | | | | | |
| | | | | **Carbonation** | -27,9 | **Carbonation** | -11,5 | | | | | | | |
| | | | | | *283,6* | | *-0,8* | | | 391,8 | *376,7* | *367,0* | *474,3* | *443,9* |
| | | | | **OPERATION 100 yrs** | | **DISPOSAL 0 yrs** | | | | | | | | |
| | | | | **Heating** | 389,3 | " | " | | | | | | | |
| | | | | **Carbonation** | -31,2 | **Carbonation** | 0,0 | | | | | | | |
| | | | | | *358,1* | | *10,7* | | | 477,9 | *462,8* | *453,1* | *453,1* | *433,0* |

*LCIA calculated results for concrete house A.*

## CO2 Balance House B

kg $CO_2$,eq./m² AREA 3981 m²

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **MANUFACTURE** | | **CONSTRUCTION** | | **OPERATION 40 yrs** | | **DISPOSAL 60 yrs** | | **EXT. BOUNDARIES** | | **NON-LIMITED CARBONATATION** | | | | |
| **Gypsum** | 7,9 | **Assembling** | 0,7 | **Maintenance** | 0,0 | **Disassembly** | 0,7 | Wood incin. Rest | -167,5 | **Max carb.** | **kg conc.** | **$CO_2$/conc.** | **kg $CO_{2,eq.}$** | **kg $CO_2$,eq./m²** |
| **Wood** | 31,6 | **Transport** | 7,2 | **Heating** | 155,7 | **Wood incin.** | **-85,2** | **Reforestation** | **-661,7** | 47,9% | 768320 | -11,7% | -43014 | *-10,8* |
| **Rock wool** | 12,9 | **Tent** | 2,9 | **Carbonation** | -2,5 | **Steel** | 1,4 | Incin. Emiss. Rest | 370,3 | | | | | |
| **Concrete** | 17,9 | | | | | **Concrete** | 0,3 | Incin. Emiss. House | 188,1 | **TOTAL** | | | | |
| **Steel** | 4,3 | | | | | **Gypsum** | 1,0 | | | **incl.:** | | | **100 yrs OPERATION** | |
| **Transport** | 3,6 | | | | | **Carbonation** | -8,0 | | | **Heating ,** | **Wood rest** | **&Bio. Cycle** | **Limited** | **Non-limited** |
| | *78,2* | | *10,8* | | *153,2* | | *-89,9* | | | *152,4* | *-15,1* | *-118,4* | *299,6* | *-296,7* |
| | | | | **OPERATION 60 yrs** | | **DISPOSAL 40 yrs** | | | | | | | | |
| | | | | **Maintenance** | 2,9 | " " | | | | | | | | |
| | | | | **Heating** | 233,6 | **Gypsum** | 1,5 | | | | | | | |
| | | | | **Carbonation** | -3,1 | **Carbonation** | -7,4 | | | | | | | |
| | | | | | *233,4* | | *-88,8* | | | *233,6* | *66,1* | *-37,2* | *180,7* | *-62,4* |
| | | | | **OPERATION 80 yrs** | | **DISPOSAL 20 yrs** | | | | | | | | |
| | | | | **Maintenance** | 5,7 | " " | | | | | | | | |
| | | | | **Heating** | 311,5 | **Gypsum** | 1,9 | | | | | | | |
| | | | | **Carbonation** | -3,6 | **Carbonation** | -6,6 | | | | | | | |
| | | | | | *313,6* | | *-87,4* | | | *315,3* | *147,8* | *44,5* | *221,0* | *54,7* |
| | | | | **OPERATION 100 yrs** | | **DISPOSAL 0 yrs** | | | | | | | | |
| | | | | **Maintenance** | 8,6 | " " | | | | | | | | |
| | | | | **Heating** | 389,3 | **Gypsum** | 2,4 | | | | | | | |
| | | | | **Carbonation** | -4,0 | **Carbonation** | 0,0 | | | | | | | |
| | | | | *394,0* | | | *-80,3* | | | *402,6* | *235,1* | *131,8* | *131,8* | *125,0* |

*LCIA calculated results for wooden house B .*