LICENTIATE THESIS NO. 12

Life cycle assessment and life cycle cost analysis of a single-family house

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Reesbe
Resource-Efficient Energy Systems in the Built Environment

The research groups that participate are Energy Systems at the University of Gävle, Energy and Environmental Technology at the Mälardalen University, and Energy and Environmental Technology at the Dalarna University. Reesbe is an effort in close cooperation with the industry in the three regions of Gävleborg, Dalarna, and Mälardalen, and is funded by the Knowledge Foundation (KK-stiftelsen).

Cover illustration: The front cover illustration shows a single-family house in Hinsnoret, a semi-rural area between Falun and Borlänge. Source: Dalarnas Försäkringsbolag (2019).

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“This new world should be the world in which the strong won’t exploit the weak, the bad won’t exploit the good, where the poor won’t be humiliated by the rich. It will be the world in which the children of intellect, science, and skills will serve the community in order to make lives easier and nicer. And not the individuals for gaining wealth. This new world can’t be the world of the humiliated, the broken but the world of free people and nations equal in dignity and respect for a man”

– Nikola Tesla

Abstract

The building industry is responsible for 35% of final energy use and 38% of CO_2 emissions at a global level. The European Union aims to reduce CO_2 emissions in the building industry by up to 90% by the year 2050. Therefore, it is important to consider the environmental impacts buildings have. The purpose of this thesis was to investigate the environmental impacts and costs of a single-family house in Sweden. In the study, the life cycle assessment (LCA) and the life cycle cost (LCC) methods have been used by following the “cradle to grave” life cycle perspective.

This study shows a significant reduction of global warming potential (GWP), primary energy (PE) use and costs when the lifespan of the house is shifted from 50 to 100 years. The findings illustrate a total decrease in LCA outcome, of GWP to 27% and PE to 18%. Considering the total LCC outcome, when the discount rate increases from 3% to 5% and then 7%, the total costs decrease significantly (60%, 85% to 95%). The embodied carbon, PE use and costs from the production stage/construction stage are significantly reduced, while the maintenance/replacement stage displays the opposite trend. Operational energy use, water consumption and end-of-life, however, remain largely unchanged. Furthermore, the findings emphasize the importance of using wood-based building materials due to its lower carbon-intensive manufacturing process compared to non-wood choices.

The results of the LCA and LCC were systematically studied and are presented visually. Low carbon and cost-effective materials and installations have to be identified in the early stage of a building design so that the appropriate investment choices can be made that will reduce a building’s total environmental and economic impact in the long run. Findings from this thesis provide a greater understanding of the environmental and economic impacts that are relevant for decision-makers when building single-family houses.

Keywords: Building, carbon-dioxide equivalent emissions, global warming potential, primary energy use, life cycle assessment, life cycle cost.

Sammanfattning

Byggbranschen svarar för 35% av den slutliga energianvändningen och 38 % av koldioxidutsläppen på global nivå. Europeiska unionen strävar efter att minska koldioxidutsläppen i byggnadsindustrin med upp till 90% fram till 2050. Därför är det viktigt att beakta byggnaders miljöpåverkan. Syftet med denna avhandling var att undersöka miljöpåverkan och kostnader för ett enfamiljshus i Sverige. I studien har livscykelbedömningen (LCA) och livscykelkostnadsmetoderna (LCC) använts genom att tillämpa livscykelperspektivet ”vagga till grav”.

Studien visar en stor minskning av global uppvärmningspotential (GWP), användning av primärenergi (PE) och kostnader vid växling från 50 till 100 års husets livslängd. Resultaten visar en årlig minskning med 27% för utsläpp av växthusgaser och med 18% för användningen av primärenergi. Med tanke på det totala LCC-utfallet, när diskonteringsräntan ökar från 3%, 5% till 7%, minskar de totala kostnaderna avsevärt (60%, 85% till 95%). Det noteras att klimatavtrycket, primärenergianvändningen och kostnaderna från produktionssteget/konstruktionssteget minskar avsevärt, medan underhålls- / utbytessteget visar den motsatta trenden när man byter från 50 till 100 års livslängd. Den operativa energianvändningen, vattenförbrukningen och avfallshanteringen är fortfarande nästan samma när man ändrar livslängden. Vidare betonar resultaten vikten av att använda träbaserade byggmaterial på grund av lägre klimatpåverkan från tillverkningsprocessen jämfört med alternativen.

LCA- och LCC-resultaten studerades systematiskt och redovisades visuellt. De koldioxidsnåla och kostnadseffektiva materialen och installationerna måste identifieras i ett tidigt skede av en byggnadskonstruktion genom att välja lämpliga investeringsval som kommer att minska de totala miljö och ekonomiska effekterna på lång sikt. Resultaten från denna avhandling ger ökad förståelse för miljömässiga och ekonomiska konsekvenser som är relevanta för beslutsfattare vid byggnation av ett enfamiljshus.

Nyckelord: Byggnad, koldioxidekvivalenta utsläpp, global uppvärmningspotential, primärenergianvändning, livscykelbedömning, livscykelkostnad.

Acknowledgements

The work presented in this thesis is part of a collaboration between Dalarna University, the University of Gävle, Dalarnas Försäkringsbolag (insurance company) and Fiskarhedenvillan (building company). Firstly, I would like to express sincere gratitude to my supervisors Ola Eriksson, Jonn Are Myhren, Xingxing Zhang and Marita Wallhagen for their excellent support and guidance throughout my PhD journey. In addition, I would like to give special thanks to Johan Pettersson and Tommie Lindkvist for guiding and inspiring me through my work at the company Dalarnas Försäkringsbolag. I would also like to thank the project leader of Dalarnas Villa, Johan Apel and all of my colleagues from Dalarnas Försäkringsbolag, Dalarna University and the University of Gävle.

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Abbreviations

BBR	Boverkets byggregler (The National Board of Housing, Building and Planning’s building regulations)
CO2e	Carbon-dioxide equivalent
EU	European Union
EPD	Environmental product declaration
GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life cycle assessment
LCC	Life cycle cost
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
PV	Present value
PE	Primary energy

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Introduction

Background

The building industry accounts for approximately 35% of final energy use and 38% of CO_2 emissions globally with the residential sector as the most responsible [1], presented in Figure 1. The significant amount of emissions is due to the large amount of fossil fuels used to supply energy to this sector. Direct emissions refer to those coming from the manufacture of building materials such as cement, steel and glass, while indirect emissions are derived from power generation used for heating and electricity.

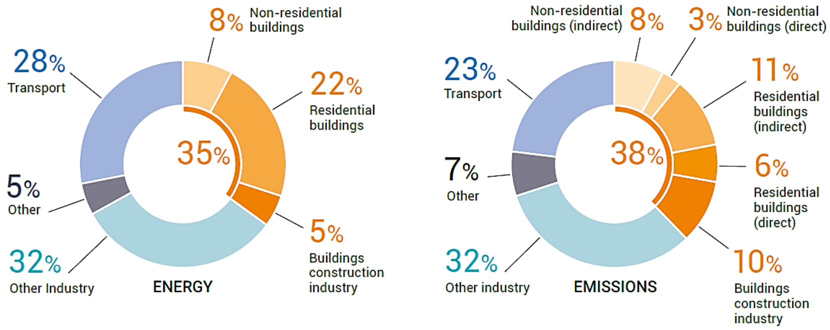

Figure 1. Global share of final energy use and CO_2 emissions in the building industry [1].

At the global level, emissions resulting from the building industry have decreased in 2020 by 10-25% compared to 2019 due to the impact of covid-19 [1]. In order to achieve a low-carbon and resilient society, improving the building industry can play a significant role in reducing energy use and greenhouse gas emissions [1]. The European Commission has an objective to reduce CO_2 emissions from the building industry by up to 90% by 2050 [2], [3]. In order to achieve these environmental goals, the building industry needs to carry out life cycle assessments (LCAs) for entire buildings, estimate environmental impacts and focus on mitigating these [4]. Due to their large primary energy (PE) use and carbon dioxide equivalent (CO_2e) emissions, buildings need to be designed so that they use greater amounts of low-fossil carbon and low-energy demand materials. Globally, of the production of building materials, cement and steel are responsible for the highest embodied carbon emissions [1]. The building industry accounts for around 50% of the global demand for cement and 30% of steel materials [1]. Therefore, it is important to find sustainable alternatives and replace high carbon with low carbon materials. Recently, the

Nordic countries have shown a strong interest in using the LCA approach for an analysis of the environmental impact of buildings [5].

Sweden has a national objective to reduce CO_2 emissions to net-zero by 2045, an obligation imposed by the Paris agreement [6], [7]. Because there have been improvements in the climate performance of the user phase, an emphasis on the construction process has become increasingly important [8]. Besides the environmental performance of building products, there is also a need for economic evaluation in order to provide sustainable alternatives among designers, architects, consultants, builders and other stakeholders in the decision-making process. Their challenge is to find the best solution for low carbon buildings and at the same time maintain profitability. The Swedish National Board of Housing, Building and Planning (Boverket) will introduce new regulations for new buildings from 2022 regarding climate declarations [9]. The purpose of this legislation is to mitigate the climate impacts of buildings. It will, firstly, require emissions from the production and construction phases of newly constructed buildings to be reported. Furthermore, it will stipulate the limit values for different building types and the emissions levels acceptable from a whole building in the coming years. Therefore, it is important to consider LCA as a method for the evaluation of climate impacts for entire buildings.

The first step when preparing the building industry for making more sustainable buildings in the future is, in the early stage of building design, by focusing on a significant reduction of embodied carbon impacts. The second step is to find possible alternatives when answering following questions:

- How can the most appropriate, low carbon and cost-effective building materials in the early stage of building design be selected?
- By using generic or environmental product declaration (EPD)-based data, how can more accurate results for building components be achieved?

These are common questions among researchers and stakeholders in the building industry for finding the most favorable solutions in reducing environmental impacts and costs in the long run. The calculation of environmental impacts and costs for a whole building is complicated because of its long lifespan and the complex number and range of building components.

However, alongside estimating the environmental impacts, the building industry also needs to include an economic evaluation of the building process. The life cycle cost (LCC) method has been used to calculate the long-term costs of a building. In order to reduce the uncertainty level it is important to include various economic parameters in the analysis. Most important are variable discount rates, the inflation rate, escalation rates and different building lifespans.

dominant construction processes use concrete and cement-based building materials, followed by steels.

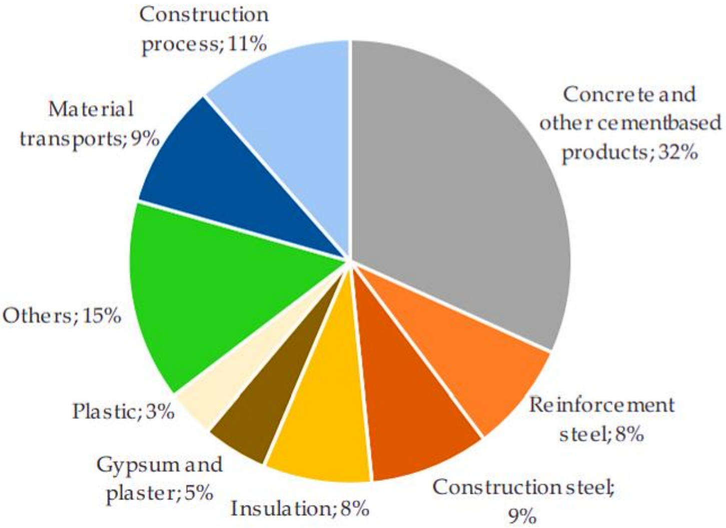

Figure 2. Carbon impact (CO_{2e}) from processes involved in the construction of buildings in Sweden [23].

In the production phase, the choice of building materials and associated energy systems has to be highlighted and integrated into all plans for mitigating life cycle energy use and climate impacts. According to Dodoo et al., a life cycle perspective is needed for a better understanding of the interactions between all of the phases of a building's life [24], [25]. The importance of using a life cycle perspective in Sweden has increased. According to the report "Climate impact of the construction process" [26], this is partly based on results showing the annually calculated GHG emissions from construction processes in buildings demonstrate around the same annual GHG emissions emitted by passenger cars [27]. Findings also demonstrate that single-family houses in Sweden have around 0.3-0.5 Mt CO_2 per year [26]. Showing how much climate impacts increase during the construction process, there is a need to investigate sustainable alternatives in the immediate future. Gustavsson et al., in a report for Boverket, advocate a comprehensive LCA for climate change mitigation in the built environment. They also discuss the difference between wood-based and non-wood materials [27].

Economic assessment of buildings

Considering the economic evaluation of long-term costs, previous studies have shown different results based on the various economic parameters used in their analyses. In the review paper by Islam et al. [28], the total LCC was calculated by using different lifespans of buildings (from 35 to 70 years, with 50 years as the average) and various discount rates (from 2-8%, with 4% as the average). Given these differing assumptions, different case studies have shown the construction stage to be the largest contributor to total LCC (58-88%), followed by the operation (11-34%), maintenance (2-20%) and disposal (0-2%) stages [28]. Furthermore, in a case study of a single-family house, the construction and maintenance costs made the largest contribution (88%) to the total LCC, while the operation and disposal stages presented only minor costs [28]. Ziemski [29] concluded that in other studies examining a single-family house with a lifespan range of 40-60 years, most average home buyers put an emphasis on initial investment costs instead of on long-term running costs. However, the study claims that by selecting energy-saving solutions during the building process, the total costs of a single-family house in the future could be lowered. Berggren et al. [30] have demonstrated that the construction phase forms the largest part of a house's total costs, or around 74%. This is followed by lower operational and maintenance costs, around 18%, and relatively minor (roughly 8%) design costs [30]. Salvado et al. [31] have done a sensitivity analysis and included additional information regarding uncertainty factors, such as discount rates, the calculation period, incomplete data for maintenance, repair and the replacement rate of building materials as well as the prediction of their costs. Furthermore, Kovacic et al. [32] have considered the parameters that influence the uncertainty level in buildings. The great impact on total LCC results have long lifespans that lead to higher uncertainty for estimation of operational costs, energy price evaluation and the choice of a discount rate [32]. The most common economic parameters used in previous studies include a discount rate, an inflation rate and various lifespans.

Relationship between environmental and economic impacts and research gap

The relationship between LCA and LCC outcomes in buildings is a complex process. Most existing studies have used separate evaluations for each method and have faced a challenge when combining them into a single unit. For example, in the paper by Fawcett et al. [33] an estimation of costs and environmental impacts were linked in the same framework by presenting fundamental differences, with the aim to support a wider and supportive discussion process. Furthermore, in the case study by Ramírez-Villegas et al. [34], no correlation between CO_2e emissions and cost was found for energy efficient renovation of multi-family buildings. However, Bartlett et al. [35] considered a total LCC, which included the environmental impact of buildings and stated the importance of including both approaches for achieving sustainable decisions over the long term. According to Bogenstätter, decisions made in the early design stage could affect up to 80% of the operational costs as well as having potential climate impacts [36]. In the study by Lasvaux et al. [37] the relationship between costs and emissions for the building elements of four dwellings were investigated. According to their related study [38], they tried to combine environmental and economic indicators within a single unit by focusing on the end-of-life stage. The objective was to support the decision-making process among various alternatives.

Most of existing studies present the outcomes of LCA and LCC approaches separately without considering the possible relationships between them and without visualizing the combined results. In many of the published case studies that deal with Swedish buildings, there is a lack of information on CO_2e emissions and PE use of building components [27]. Furthermore, most of the case studies evaluate LCA and LCC for multi-family buildings and offices, while single-family houses have not been fully considered.

Aim and research questions

This thesis is motivated by the fact that energy use and carbon emissions within the building sector are steadily on the increase. In order to enable this sector to meet climate goals and investigate primary energy reduction the global warming potential (GWP) and primary energy (PE) use indicators were explored. Another objective underlying this study is to evaluate emissions within various time horizons and discuss how these meet the requirements for climate declarations in Sweden. In the thesis, the aim was to investigate GWP and PE use and calculate the financial costs for a single-family house from a lifecycle perspective. Its aim was also to provide a combination of both results that would be relevant for a variety of decision-makers in the building industry, including, for example, designers, investors, architects, consultants, and manufacturers. With these objectives in mind, three research questions were developed:

1. How can the evaluation of GWP, PE use and costs vary for the different life cycle stages of a single-family house?

2. What are the implications of different building lifespans?

3. How can different building components be compared and evaluated from an environmental and economic point of view?

Methodology

Life cycle assessment

Life cycle assessment is a method for evaluating the environmental impact of a building, from the production phase, through the construction phase, use phase and on until the building's end-of-life according to ISO 14040 standard [39]. This method can be used at a micro level, to investigate the environmental impact of a single product or building, and at a macro level, to examine the impact of the building industry as a whole for policy-making purposes. The LCA framework consist of four main stages, here presented in Figure 3:

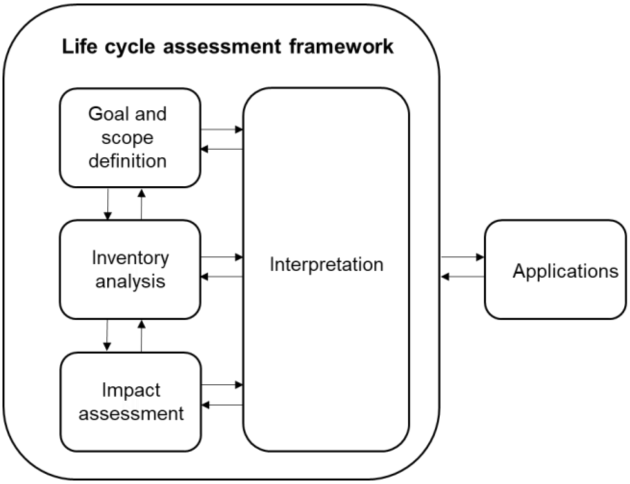

Figure 3. Life cycle assessment framework according to ISO 14040 [39].

In the first phase, goal and scope definition, the functional unit, system boundary, and impact categories are introduced. The functional unit can be defined as the common unit used for comparison so that the results of one LCA can be compared to another on a product/building level. For instance, different functional units can be used, such as m^2 per total gross floor area/heated area or the whole building. The system boundary defines activities and processes that will be included in the LCA analysis. In the second phase, the life cycle inventory (LCI), the use/need of materials and processes and associated emissions and raw material extraction are summarized. The LCI analysis includes data collection based on material and energy flows that occur during the product life cycle. Program tools and databases have a significant role, as it is almost impossible when performing an LCA to evaluate each material and process from each individual project every time. Databases provide generic and/or product-specific data. The third phase in the LCA framework is the life cycle impact assessment (LCIA) that is based on inventory data transferred to specific impact categories. During this stage, the inventory parameters have to be sorted according to type of environmental impact, a process called classification. The next step is characterization, describing the relative contribution of emissions to each environmental impact. The most common impact categories based on CML/EN/TRACI methods are global warming potential, ozone deletion potential, acidification potential, eutrophication potential, photochemical ozone creation potential, and abiotic depletion potential. [40]. In the final phase, interpretation, the LCI and LCIA are summarized and analyzed. This stage is informative and intended to support decision-makers in finding the best solution [41].

Life cycle cost

Life cycle cost analysis is a method for calculating the financial costs that occur during the entire life of a product, in this case a building. Different economic parameters are needed in order to make cost-effective decisions. LCC provides the opportunity for an evaluation of long-term costs. The most common method for calculating LCC is the present value (PV) method, which adjusts future cash flows to their present values:

$$\mathrm{PV} = \mathrm{F_t} \times \frac{1}{(1+\mathrm{d})^{\mathrm{t}}}$$

PV= Present value
t = Time in units of year
F_t = Future cash amount that occurs in year t
d = Discount rate used for discounting future cash amounts to the present value.

The general LCC formula was used to summarize the cradle-to-grave costs that occur in a building:

$$\mathrm{LCC} = \mathrm{I} + \mathrm{Repl} + \mathrm{E} + \mathrm{W} + \mathrm{EOL}$$

I – Investment costs
Repl – Replacement costs
E – Operational energy costs
W – Operational water costs
EOL – End-of-life costs

LCC involves making comparisons between different alternatives that consider all related costs. The main parameters used in the calculations are inflation rate, discount rate and the lifetime of a building. Accurate results depend on the quality of the data collection and the parameters used in the calculations.

Life cycle stages and modules

Table 1 follows the EN 15978 [42] and EN 15804 standard [43] (A1-C4) for conducting the LCA. These are also in line with the ISO 14040 standard [39]. For the LCC, the calculations follow the EN 16627 standard [44] (A0-C4) and ISO 15686-5 [45] (Table 1).

Table 1. Life cycle stages according to EN 15978 and EN 16627

Life cycle stage	**Module**	
Pre-construction stage	Costs to purchase/rent the land	A0
Production stage	Raw material supply	A1
	Transport	A2
	Manufacturing	A3
Construction process stage	Transport to the building site	A4
	Installations into building	A5
Use stage	Use/application	B1
	Maintenance	B2
	Repair	B3
	Replacement	B4
	Refurbishment	B5
	Operational energy use	B6
	Operational water use	B7
End-of-life stage	Deconstruction/Demolition	C1
	Transport	C2
	Waste processing	C3
	Disposal	C4

- The pre-construction stage (A0) includes only the costs for purchasing the land and other municipal costs, such as taxes and fees.
- The production stage (A1-A3) includes the emissions and costs of the raw material supply, transportation to the manufacturing site and the process of turning them into building materials and energy systems.
- The construction stage (A4-A5) calculates the emissions and costs associated with transportation of the building materials from the manufacturing site to the building site. It also considers the energy use, water use and waste processes occurring during the construction process.
- The use stage (B1-B7) includes the emissions and costs relating to the maintenance and replacement of building materials, as well as operational energy and water use.
- The end-of-life stage (C1-C4) includes the emissions and costs occurring during the deconstruction of a building. This includes transportation, waste processing and disposal.

Framework of the LCA and LCC

Figure 4 shows the framework of the environmental, energy and economic assessments and the connections between them. The input data included in the LCA and LCC were evaluated using the software One Click LCA. The software comes with its own databases, such as a list of the EPDs and average data for building materials from manufacturers across the world. An EPD document represents a detailed description of the environmental impact of a product. Most EPDs are based on the EN 15804 standard [43]. Many manufacturers have produced data according to national specifications. The costs associated with the transport of building materials to the building site were calculated by combining the distance from locally based building supply stores and One Click LCAs own default data. The figures used to calculate the costs of replacing building materials and installations are in the range of 20-60 years. In particular, roof replacement was set at 60 years, wood panels, windows, and ventilation system at approximately 50 years; solar panels and parquet at 30 years and heat pump at 20 years. Additionally, the sensitivity analysis used different timeframes in order to investigate the relationship between GWP, PE use and costs.

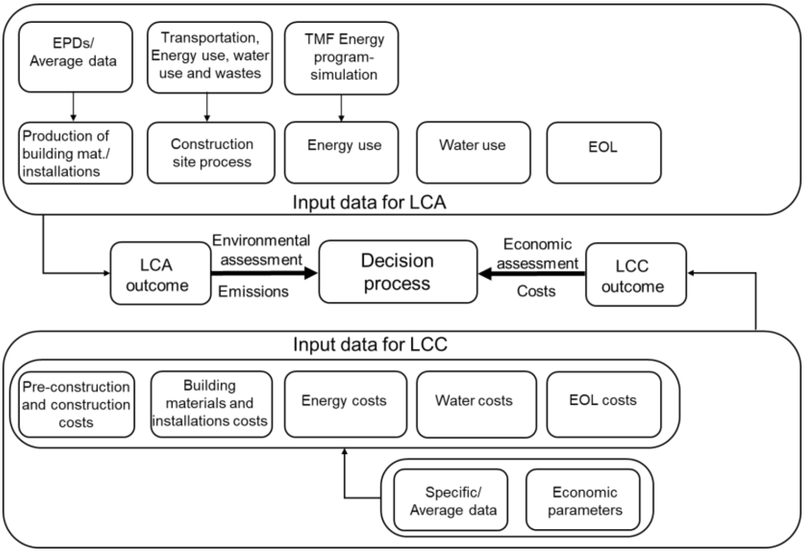

Figure 4. Framework of the two methods used in this thesis and the connections between them

Paper I: Applying a LCA method

Due to the lack of information on CO_2e emissions and PE use for single-family houses in Sweden and given the intention of the Swedish building industry to mitigate climate impacts, Paper I carried out a comprehensive LCA by following a cradle-to-grave approach. In Paper I the calculations were made using One Click LCA software, which is compliant with the EN 15978 standard and

Table 4. Output data on energy use as simulated in the TMF Energy program (Paper I)

Output on energy use	Value	Unit
Specific energy use (bought energy excl. household/A_{temp})	31.5	kWh/m^2/y
Primary energy (PE)*	45.3	kWh/m^2/y
Primary energy (PE) requirement level BBR 25 (BFS 2017:5)	90	kWh/m^2/y
Energy level BED 9 (BFS 2016:14)	B	-
Total energy demand	26 331	kWh/y
Energy use: heat pump	16 562	kWh/y
Energy supply: PV system (solar cells)	5 074	kWh/y
Total purchased energy	4 695	kWh/y
Specific energy use (bought energy excl. household/A_{temp})	31.5	kWh/m^2/y

Note: In this Swedish scenario, primary energy is calculated with a primary energy factor of about 1.6 kWh/m2/y.

Table 5. Economic parameters used in the calculations (Paper II)

Economic parameters	Input	Source
Inflation rate	2 %	Riksbank, Sweden's central bank
Discount rates	3 %, 5 % and 7 %	Nominal discount rate 5 % (Dalarnas Försäkringsbolag)
Water inflation rate	2 %	Default data from the software One Click LCA
EOL as % of capital costs	2.5 %	Default data from the software One Click LCA
Electricity price	1.56 SEK/kWh	Eurostat (average price for period 2009-2019), including taxes for household consumers in Sweden
Water price	23.6 SEK/m^3	Calculated for a family using 200 m^3/y and including Swedish taxes
Lifespan	50 and 100 years	Assumed time horizons

Results

In this section, the main results of the LCA and LCC analyses are presented. Those that are most relevant for decision-making purposes are discussed separately. This is then followed by a graphic visualization of all of the results integrated together. A more detailed analysis of the LCA and LCC for this case study is presented in Papers I and II.

Life cycle assessment

Figure 6 shows the use of GWP and PE use across the life cycle at the 50 and 100-year lifespan. Findings show that when shifting from a 50 to a 100-year lifespan, the reduction of CO_2e emissions is 27% while for the PE use the decrease is 18%. It is noticeable that the GWP shows a significant reduction from 3.6 to 1.7 kg CO_2e/m^2/y and the PE use from 73.3 to 30.1 MJ during the production stage. The opposite trend is found during the maintenance/replacement stage, where GWP shows an increase from 1.2 to 2.1 kg CO_2e/m^2/y and the PE use from 35.8 to 48.3 MJ. This is mainly due to the replacement rate of solar panels. While changing the lifespan results in large differences in the construction stage, this does not make a significant contribution to the overall results. The high demand for PE use is found during the operational phase of the building, while the operational water and end-of-life stages are of minor importance when considering both indicators.

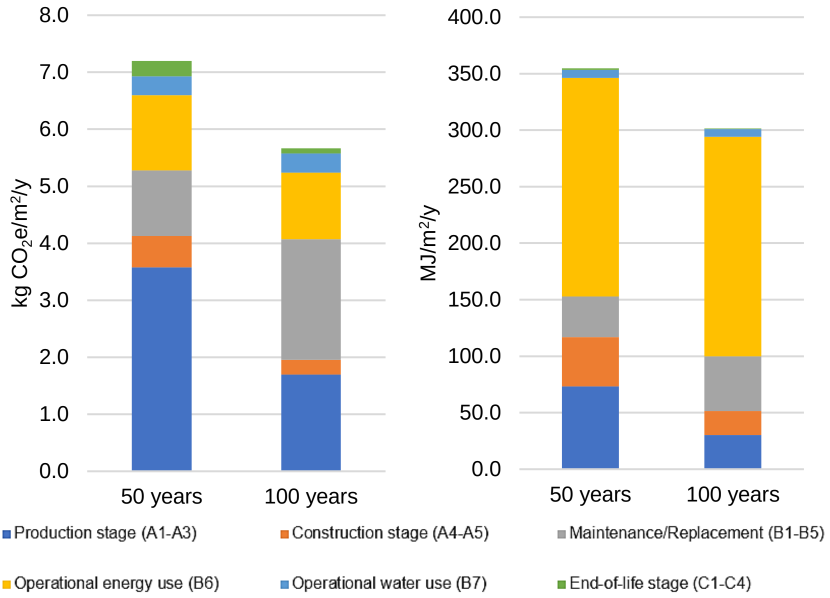

Figure 6. Total share of GWP and PE use across two possible life cycle lifespans.

Life cycle cost

Figure 7 demonstrates the total LCC by taking into account the undiscounted costs. It also shows the results of the sensitivity analysis by using different discount rates for 50 and 100-years lifespans. Without taking a discount rate into consideration, the findings show a 27% higher total LCC when shifting from a 50 to 100-year lifespan. That said, when different discount rates are applied, the LCC results display different outcomes. When the discount rate increases from 3% to 5% and then 7% and the lifespan is increased from 50 to 100 years, the total LCC decreases significantly (60%, 85% to 95 %). It can be observed that the construction costs distributed per year are significantly reduced and rendered insignificant by the changing discount rates. They are already given in the present value and did not need discounting process, while the running costs and end-of-life costs decrease gradually.

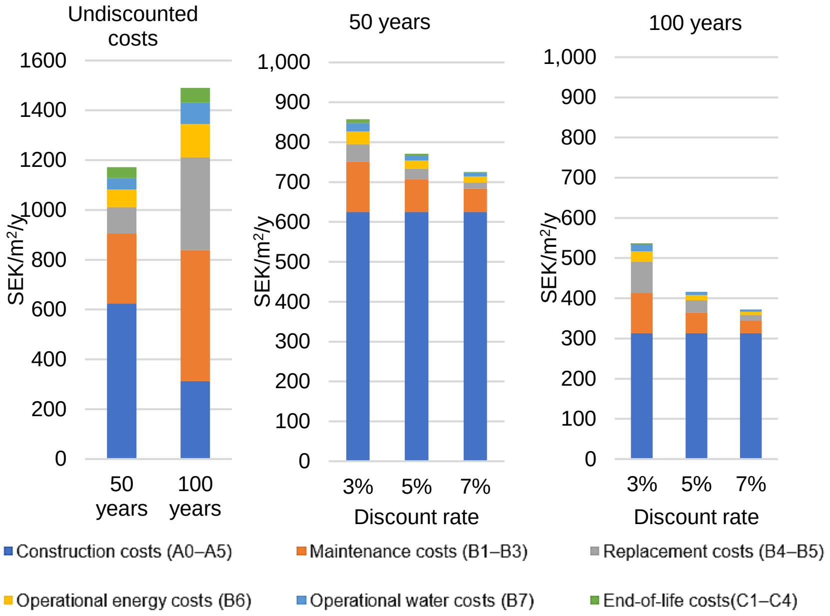

Figure 7. Comparative LCC results showing undiscounted costs and different discount rates for two lifespans.

Combined LCA and LCC outcomes

Figure 8 represents the combination of the LCA and LCC results as visualized within a single graphical outcome. The combined LCA and LCC outcomes are plotted together as the total share of GWP, PE use and undiscounted costs. It can be observed that, when shifting from a 50 to 100-year lifespan, the share taken up by the production/construction stage is significantly decreased for all three parameters, while the share occupied by the maintenance/replacement stage is increased. The operational energy use, water consumption and end-of-life costs remain nearly the same across both lifespans.

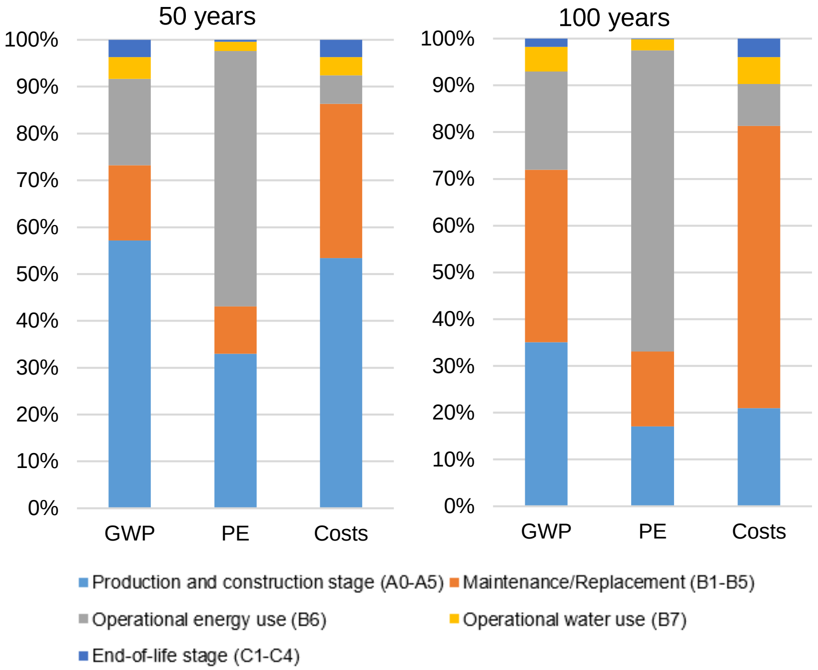

Figure 8. Combined GWP, PE use and costs for 50 and 100-year lifespans.

In Figure 9, the relationship between GWP, PE use and costs for building components are considered. The analysis indicates that most materials have reached "consensus" (meaning a positive linear correlation for CO_2e emissions and costs) and could be considered as environmentally and economically favorable solutions. However, it is interesting to notice that some low-cost products are not always environmentally friendly alternatives. The largest gap is found during the production of concrete and solar PV panels. Both of these contain extremely high levels of embodied carbon, even though they are recognized as low-cost solutions. The wood-based products in this study have shown very low levels of embodied carbon, followed by low PE use and costs in total share. Solar panels have demonstrated the highest share of PE use followed by pipes, windows and gypsum.

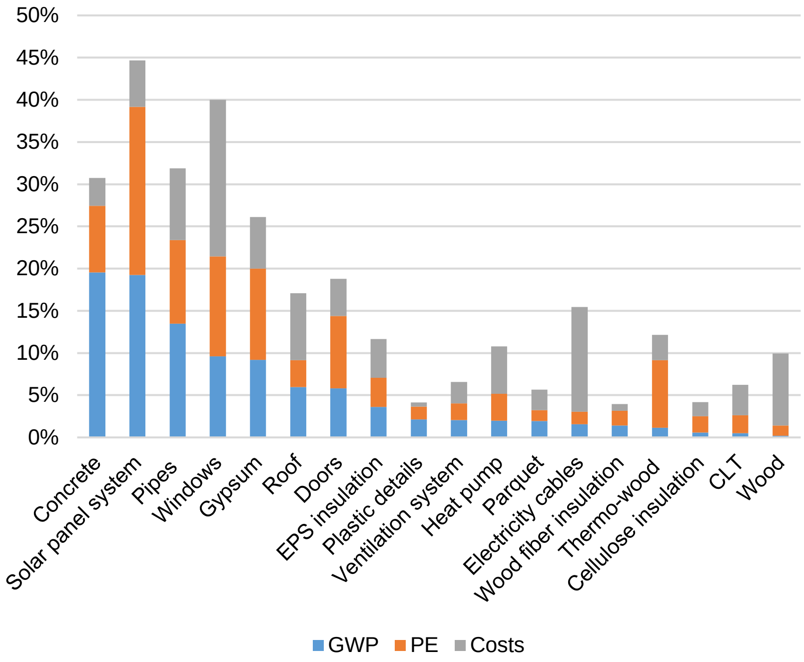

Figure 9. The assessment of building components: GWP, PE use and costs.

Discussion

The aim of this work was to evaluate the LCA and LCC outcomes for a single-family house that included different parameters. This study investigated the environmental, energy and economic assessments within different life cycle stages and included an elaborate sensitivity analysis of building components. It can be pointed out from our study that investing in a 100-year lifespan for a house has positive benefits. The GHG emissions, PE use and economic impacts per square meter on an annual basis are significantly lower than those for a 50-year lifespan. According to these findings, it can be concluded that investing in the early phase of a building's design, by selecting low carbon building materials and energy efficient systems, will lead to lower costs in the long term.

Given that regulations on climate declarations for newly constructed buildings will come into force in Sweden from 2022, it is also valuable to mention some reference values proposed by other countries to compare with our findings. In the report issued by Bionova [50] countries such as Austria, France, the Netherlands and Norway are recognized as good examples of best practice for the implementation of plans that seek to reduce carbon impacts from the building industry. For instance, France [50] set carbon limits to 14 kg $CO_2e/m^2/y$ for single-family houses, while Finland [51] proposed 15.5 kg $CO_2e/m^2/y$ for residential buildings with a 50-year lifespan. In comparison to these values, the findings produced in this study show half the emissions for the same time period. As a result of an examination of 133 building cases, Norway set an initial benchmark value for all building types in the as-built phase in the range 4-8.2 $kgCO_2e/m^2/y$ for a 60-year lifespan [52]. Lasvaux et al. assessed 40 single-family houses and proposed an average value of GHG for the French building industry of 8.4 kg $CO_2e/m^2/y$ [53]. Their findings also recognized that wood-based houses had the lowest carbon footprint and PE use, while concrete-based houses displayed the highest level of GHG emissions, with more than 20 kg $CO_2e/m^2/y$.

In this thesis, the undiscounted costs were added and considered as a comparable unit because the LCA outcomes were not under a discounted scheme. The discounting method is mostly used when converting future costs to a present value; the same method is not a common approach when calculating emissions. Thus, Schmidt et al. outlined an economic assessment of GHG emissions by using the discount method to calculate the present value of GHG emissions [54]. Furthermore, they investigated a capitalization approach by multiplying GHG emissions with the price of carbon. These approaches could introduce researchers to and encourage them to apply a sensitivity analysis by using a discounting scheme and "translating" environmental impacts into an economic value. Additionally, Schmidt et al. [55] addressed gaps and disadvantages in developing potential trade-offs between environmental and economic approaches. In the review [38] a multi-criteria analysis is recommended so that trade-offs between the LCA and LCC approaches can be elucidated. In addition, focusing on better choices of products and processes by balancing the impacts from both perspectives will provide higher quality information for decision makers and the decision-making process.

Environmental, energy and economic relationships of building components

From an environmental and energy perspective, wood-based materials are considered as sustainable construction materials with very low embodied fossil carbon [55] and PE use. This is mainly due to their less intensive energy production process. Non-wood materials could be cheaper, but they still show significantly higher environmental impacts. Wallhagen et al. have shown that the concrete used for foundations has the highest impact rating, followed by glass and steel materials [56]. Imbabi et al. also demonstrate that the energy intensive cement production contributes to concrete's high GHG emissions. Replacing ordinary cement with a green alternative could reduce its emissions levels by up to 95% [57]. Sustainable concrete material with a low carbon production process, such as one of the new cement aggregates currently being developed using energy efficient technologies, could minimize concrete's embodied carbon [57]. Other sustainable solutions might be effective to further reduce the CO_2e emissions of building materials. For instance, when examining Dalarnas Villa, the cellulose insulation used there, in comparison with either glass or stone wool insulation, demonstrated a significantly lower level of carbon emissions during its production process [58]. One of the reasons why glass and stone wool insulation have a higher level of embodied carbon is based on the intensive manufacturing process that they must undergo. That said, from an economic perspective, cellulose insulation costs at least twice as much as other insulation options [40]. Thus, ecological materials are sometimes not economically justified.

When considering energy output, the heat pump is considered to be an energy efficient energy system, primarily because its manufacturing process generates relatively low levels of embodied emissions (Figure 9). However, as the study of Dalarnas Villa showed, there is a considerable amount of embodied carbon in the PV panels. Their high "carbon footprint" is the result of the fact that they are produced in Europe, with its higher production costs, and consist of metals that need an energy intensive production process. Solar PV panels also need to be replaced approximately every 30 years [58], meaning they have around three times the replacement costs for a 100-year lifespan. This increases their total embodied carbon significantly. Investing in a ventilation system with a replacing rate of approximately 50 years and a heat pump with a 20-year replacement rate, demonstrates a significantly lower carbon impact than solar panels [58].

When comparing the latest data from 2019 for electricity generation, the European average emissions of 255 gCO_2e/kWh demonstrate significantly higher operational carbon compared to the Swedish electricity mix that emits only 12 gCO_2e/kWh. [59]. Ramírez-Villegas confirms that both costs and emissions from the Swedish electricity grid are considered lower than the EU levels [60]. Because Sweden intends to fully decarbonize its electricity grid in the short term, the implementation of solar PV panels could be encouraged in countries based on the carbon intensity of their electricity grid. This could influence the reduction of operational carbon. Moreover, when the solar PV panels reach their end-of-life, they could be recycled, thus reducing the embodied carbon for the production of new panels. The study by Latunussa et al. shows that the processes/subsystems making the largest impacts during the recycling process are related to the transportation of solar PV panel waste to the treatment site as well as the additional processes of incineration and metal recovery [61]. According to the LCC results presented in Paper II, solar panels are profitable solutions, which could significantly decrease long-term operational costs. The assumed scenario in Paper II – which did not include installed solar panels - led to significantly higher operational costs.

When performing an LCA, data selection plays a crucial role. One of the identified challenges when considering total emissions is collection of all data needed and include them in the calculations. This is the reason why data quality plays a significant role in an LCA process. One of the main challenges in the building design process is to find appropriate and reliable environmental data for building materials and energy systems. In the early stage of a building's design, generic data can be used for an overall estimation of the environmental performance of building materials. However, for a more accurate evaluation, the specific EPDs have to be included in the LCA [62]. With accurate and detailed EPDs, manufacturers could make their products more transparent by calculating the emissions themselves, from the extraction of raw materials and their transportation to the manufacturing site to their manufacture and packaging. Users would get more accurate information and increase their ability to choose materials with low embodied carbon. However, there is still a lack of EPDs in most building databases. It is also a challenge to compare them because they are often very different. They cover different life cycle stages and include information from different environmental impacts. Some EPDs reflect national standards and are written in the local language. Others are written in English and are intended for an international audience. Thus, the data in an EPD about a product or a system are usually incomplete, incomparable and complex to follow. EPD comparability needs significant development in order for the clarity within LCI methods to be improved.

Time perspectives

In Sweden, buildings are built to last for at least 50 years. If the lifespan of a building is long, the accuracy of the results is lower because genuine uncertainties have appeared during its occupancy. Therefore, an uncertainty analysis is necessary to reduce risk. In the early stage of a building's design, it is hard to predict which installations and building materials will need maintenance/replacement. Many factors can influence this, such as the nature of the product, its service life, occupancy preferences and technological improvements. In this study, building materials and installations were assumed to be replaced with products that had the same characteristics as ones that could be purchased "today". Thus, it is possible to discuss which installations are environmentally and economically feasible in the long term when taking into account the same technical properties. One of the main issues is estimating costs that appear after the construction process has completed. Due to the long lifespan of a building, costs related to maintenance, replacement and repair are hard to predict. Replacement of building materials and installations depends on their service life. If a building has a long lifespan, it is clear that the components will have to be replaced more often, thus increasing the total costs as well as the emissions. In this study, the highest environmental impacts occurred during the production of building components. This was because high-intensity manufacturing processes were used only to produce the concrete for the foundations and the solar PV panels [58].

One of the key parameters used in this study is the decision to set the initial lifespan of the building at 100 years and then to include another lifespan of 50 years that could be used in a sensitivity analysis to examine the deviations. The findings from the thesis on this basis are in line with other findings for single-family houses. In the study by Lasvaux et al., depending on which part of the building is evaluated, the overall impacts are reduced from -2 to -47% for GWP and PE use indicators [53] when comparing a 50 with a 100-year life period.

The other issue is that despite relatively stable energy prices in Sweden over the past number of years, it can be a challenge to predict large-scale energy transition in the building industry over a long time period, as was the case in this study. In the future, it is likely that energy prices will be more localized and increasingly influenced by ever-higher proportions of renewable energy in the energy grid. The electricity price often varies from summer to winter, from the national to the regional level, and it can differ for different building types. Therefore, it is valuable to have a range of energy escalation and some mech-anism for predicting the fluctuation of energy prices (Paper II).

Conclusions

The main aim of this work was to investigate environmental impacts, PE use and costs by following a life cycle approach. Using a sensitivity analysis and testing for different alternatives has reduced the risk of future uncertainties. Investing more in the initial phase of a building's construction, by choosing the appropriate parameters, is likely to decrease the embodied emissions, PE use in materials and construction costs. Decision-makers in the building industry, therefore, should spend more time and effort on the initial phase of designing a building, by selecting more sustainable building materials and discovering the most appropriate solution.

The results from using the LCA and LCC methods show there is a significant reduction in GWP, PE use and costs in the production/construction stage when shifting from a 50 to 100-year lifespan. Results from the maintenance/replacement stage, however, have shown the opposite trend. Therefore, it is crucial to encourage decision makers to include low carbon and profitable components in the early stage of a building's design and thus reduce its total impacts in the long term.

Finally, in this study the LCA and LCC outcomes have been combined and presented visually as is illustrated in the thesis. The share of total emissions, PE use and undiscounted costs were presented visually in order to find correlations between all three indicators. It can be also pointed out that in comparison to the annual assessment used in the thesis, analyzing results per square meter, as it is presented in Paper II, provide a different angle of interpretation.

Future research

It can be concluded that there is still “room” for researchers to investigate LCA and LCC and find more correlations. It could be interesting to investigate the relationship between environmental and economic impacts of different energy systems related to single-family buildings and identify the most appropriate solution. In addition, how the “leftovers” from the demolition of a building after it has reached its end-of-life presents some questions for further investigation. Therefore, it could be interesting to investigate the impacts of reusing and recycling of secondary materials and installations after their end of service life and how they could be used in new buildings. These issues could help the building industry to test and find solutions for increasing the service life of building materials and reducing waste. In that context, calculating and estimating emissions and costs that occur after the end-of-life of a building will contribute to valuable discussions around circularity. Another undeveloped research area would be to explore energy components on deeper level by measuring and comparing the environmental performance and cost-effectiveness of different energy systems.

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