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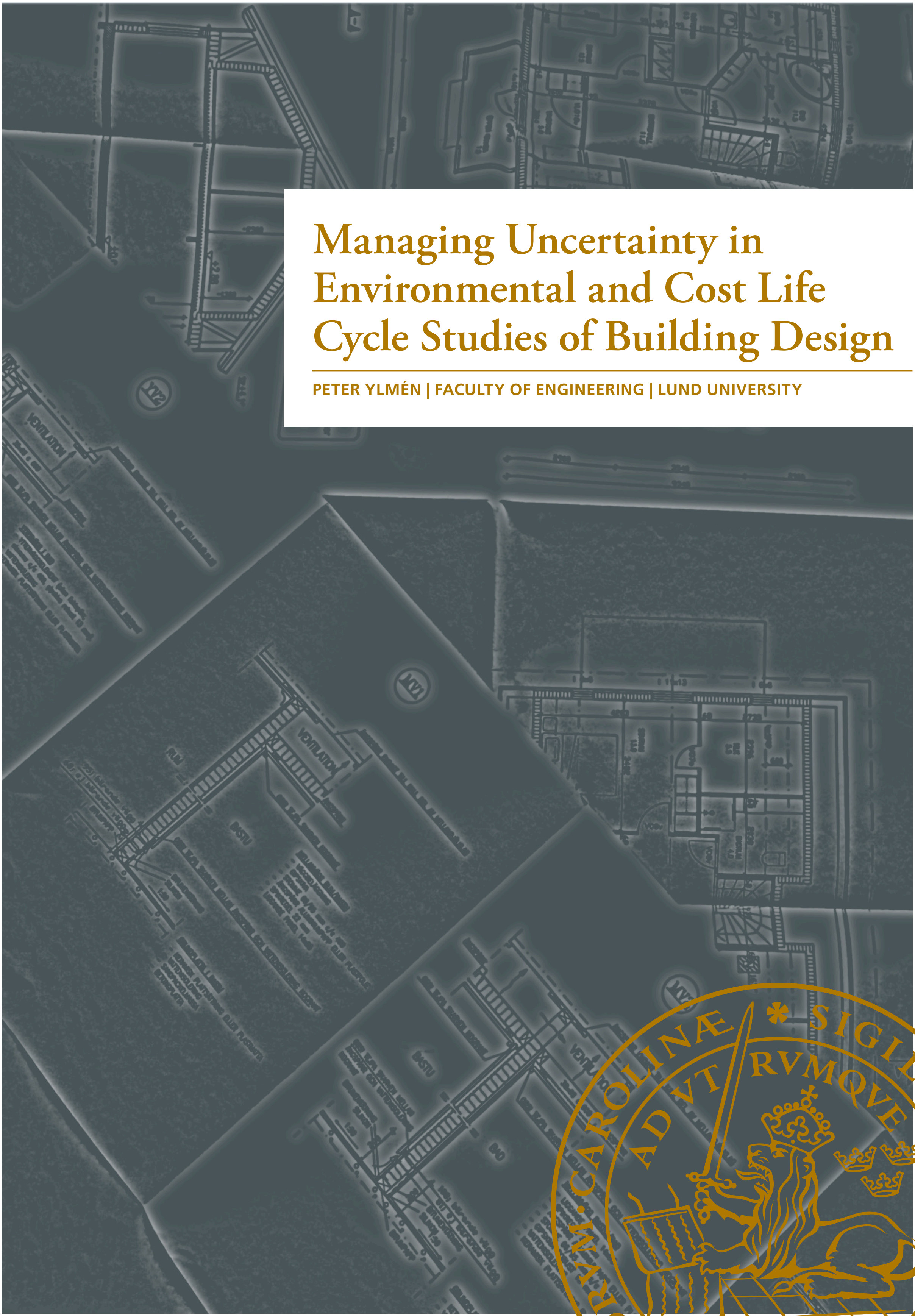

Managing Uncertainty in Environmental and Cost Life Cycle Studies of Building Design

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Abstract

In order to mitigate global warming and address other pertinent environmental issues, it is important to reduce the environmental impact from the building stock. Emissions can be large for both operational energy consumption and production of materials. It is therefore important to find building design solutions that consider production, operation and maintenance in order to minimise the climate impact of a building during its entire lifetime. At the same time, the production of buildings has to be cost-efficient. In the design of buildings, both environmental impact and cost must be evaluated in order to make well-supported decisions.

There are many uncertainties in the design phase of buildings. This study explored the uncertainties that occur when a life cycle perspective is adopted in building design decisions and developed an approach to manage them. Addressed issues were secondary effects of design changes, material data gaps and how subjective choices and parameter uncertainties can be managed in conjunction. This was done by developing the Effect and Consequences Evaluation (ECE) method and the Decision Choices Procedure (DCP), which were combined into a general approach. The presented approach will provide a structured means to set up system boundaries and manage uncertainties when life cycle studies are used as decision support for optimising building design. Several case studies were carried out to penetrate specific issues, and the final approach was demonstrated with a case study of selecting optimal insulation thickness when designing the building envelope.

The results can be used to support decisions on where and how to effectively make improvements when subjective choices and parameter uncertainties are considered in the study. This will facilitate decisions on different building design solutions so that the option with the lowest total environmental impact and a reasonable cost can be chosen.

Key words: Building design, life cycle, LCA, LCC, uncertainties, method

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II *The influence of secondary effects on global warming and cost optimization of insulation in the building envelope*
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Publications by the author related to the topic but not included in this thesis:

Experiences with LCA in the Nordic Building Industry – Challenges, Needs and Solutions
Schlanbusch R.D., Fufa S.M., Häkkinen T., Vares S., Birgisdottir H. and Ylmén P.
Energy Procedia **96**, 82-93 (2016)

Preface

In my career I have looked at several environmental aspects of buildings and building design. An especially interesting topic for me was, and still is, operational energy consumption. Several years ago, buildings started to be designed with extremely high energy performance. At this time, it began to be questioned whether the environmental impact from measures to lower the energy consumption even further could be larger than the reduction caused by the energy saved. To answer this, I decided to look into life cycle thinking in the design process of buildings. People not familiar with life cycle studies might not realise the complexity. They may believe that you can get necessary data from a database or manufacturer, put it into a software in the right way and out comes a definitive answer. At least I thought something like that when this project started. However, that is not the case. Investigating the life cycle of even simple products means that one must move outside one's area of expertise and investigate how the world affect the product life cycle and how the product affect the world. There are many methodological choices to make and there are always some data missing. I was once told that adopting life cycle thinking will make you talk about two stages of your life, before and after life cycle thinking. I am inclined to agree.

Evaluation of a building design will induce a lot of uncertainties, as there simply isn't enough time and resources to obtain all relevant data or investigate all aspects. In the design phase this problem is even larger than for a finished building. I was aware of this fact before starting this work but had never really penetrated the issue. To provide credibility to comparisons of different design alternatives I felt that this had to be addressed. This is another topic that influenced my thinking in how to approach evaluation of building design. First came an overwhelming feeling. There are so many types of uncertainties involved in such an evaluation, and I could not possible address them all. However, by consulting the literature of previously made research on the topic I found that managing choices, especially subjective choices, were a pertinent issue in this context.

My professional background is from the building sector. Hence, the work focus around the theoretical and practical issues in carrying out life cycle studies on buildings, rather than life cycle methods in a general fashion. In addition to the scientific contribution, this thesis provides an approach with a workflow that is mainly aimed at practitioners, decision-makers and other actors involved in life cycle assessment and life cycle cost analysis for building design. However, people involved or interested in design decision processes with life cycle thinking for other objects may also find it helpful.

My supervisors, Jesper Arfvidsson at LTH and Kristina Mjörnell and Johanna Berlin at RISE, have supported me throughout this thesis. They have guided me through all these years with thoughtful, steady hands. Their experience and deep knowledge have helped me to improve the quality of my work and allowed me to grow in the research profession. I gratefully thank the Development Fund of the Swedish Construction Industry (SBUF) and the Swedish Energy Agency for financial support. A special thank you to Swedish industrial partners at Skanska, The Swedish Construction Federation, PEAB, NCC, Johnny Kellner Bygg- och energikonsult, Besab and Eksta Bostads AB. Last but not least, I would like to mention my children Lia, Julian and Tina, who bring me so much joy, and my beloved wife, Jeong Lim, who lights up my life.

Landvetter, September 2020

Summary in English

The building and construction sector accounted for 39% of energy and process-related carbon dioxide emissions in 2018 and global emissions from buildings increased by 2% for the second consecutive year. It is therefore important to find building design solutions that minimise the climate impact of buildings. At the same time, the production of residential houses and commercial buildings must be cost-efficient in order to provide housing and workplaces at reasonable prices.

Several studies have recently pointed out that although the energy used for operating the buildings has a large environmental impact, the manufacturing, replacement and waste management of building material and products can represent an equally large share of the total environmental impact of buildings. It is thus important to consider the complete life cycle when evaluating the design alternatives of buildings. There is a risk of missing important environmental and economic aspects if only a portion of the life cycle is addressed during the evaluation. This will lead to faulty conclusions and sub-optimal solutions of the building design.

Available and mature life cycle tools for evaluating buildings and other products are life cycle assessment (LCA) and life cycle cost analysis (LCCA). Even for simple products, the manufacturing chain from raw material acquisition, production and use through to waste management is complex and intertwined with material flows of products outside the studied object. This means that even if the methods are mature there are many assumptions and choices to be made when evaluating the effect on for example the environment and cost of a building during its life cycle. Conducting an LCA and LCCA for products and buildings is therefore time- and resource-demanding even for products with set production lines.

It is easier to make changes in the early design stages when there are fewer decisions that have been set, and the design freedom is larger. However, this also means that there is less data to base the life cycle studies on. As there are larger degrees of freedom, there are more available options to consider. When evaluating a design alternative based on the design process information, such as which products to use, manufactures, installations, user patterns and assembly methods might not have been decided yet. Conducting LCAs and LCCAs under these circumstances naturally involves greater uncertainties in the results than for products with fixed systems.

The work described in this thesis consists of a number of studies in which methods and procedures have been developed to facilitate evaluating building design alternatives using life cycle tools. The Effect and Consequences Evaluation (ECE) method describes how to establish the technical system boundaries in a consistent way. Its focus is on managing secondary effects that arise in different parts of the building as an effect of the design alternative. The secondary effects were shown to have significant impact on the results in a case study. The Decision Choices Procedure (DCP) was also developed within the project. It provides a means to manage choices and their options in a structured way when life cycle tools are used as design decision support. Another studied issue was how to obtain reliable data on the materials and products used in buildings. A process enabling contractors to report data on site in a form that facilitates life cycle studies was explored for an office building. To demonstrate how to utilise the developed methods and procedures several case studies were conducted. Four case studies were made to evaluate each issue separately and an additional one to demonstrate how to combine the methods when conducting an LCA and LCCA, concerning how to optimise insulation thickness in a building.

The emphasis of this study has been more on accuracy of the results rather than simplification in order to mitigate erroneous conclusions regarding environmentally friendly, cost-effective alternatives for the building design. However, a simplification of life cycle studies does come from providing a structured and more consistent process of managing technical system boundaries and uncertainties in design optimisation. Adopting the approach described in this study will likely provide design conclusions with higher quality as well as save time and effort when conducting the study.

Sammanfattning på svenska

Byggnadssektorn stod för 39 % av energi- och processrelaterade koldioxidutsläpp år 2018 och globala utsläpp från byggnader ökade med 2 % för det andra året i rad. Därför är det viktigt att ta fram lösningar på byggnadsdesign som minimerar klimatpåverkan från byggnader. Samtidigt som produktionen av bostäder och kommersiella byggnader måste vara kostnadseffektiv för att skapa boende och arbetsplatser till en rimlig kostnad.

På senare tid har flera studier nyligen påvisat att även om energianvändningen för uppvärmningen och drift har stor miljöpåverkan så kan tillverkning, utbyte och avfallshantering av byggnader ha en motsvarande magnitud av byggnaders totala miljöpåverkan. Det är därför viktigt att ta hänsyn till hela livscykeln vid utvärdering av designalternativ för byggnader. Det finns en risk att viktiga utsläpp och kostnadsaspekter förbises om bara en del av livscykeln beaktas vid utvärderingen. Detta kan leda till felaktiga slutsatser och suboptimala lösningar vid design av byggnader.

Tillgängliga och beprövade livscykelverktyg för att utvärdera byggnader och andra produkter är livscykelanalys (LCA) och livscykelkostandsberäkningar (LCC). Till och med för enkla produkter är tillverkningskedjan från råmaterialutvinning, tillverkning, användning och sluthantering komplex och sammanflätade med materialflöden för andra produkter än den studerade. Detta betyder att även om metoderna har långvarig utvecklig så finns det många antaganden och val som behöver göras när miljöpåverkan och kostnader utvärderas för en byggnads livscykel. Genomförande av LCA och LCC kräver därför mycket tid och resurser även för produkter med fasta produktionslinjer.

När en byggnad designas är det lättare att genomföra ändringar i början, då färre besluts har tagits och designfriheten är större. Dock medför det även att det finns mindre data att använda i en livscykelstudie. Eftersom det finns fler frihetsgrader så är det fler val att hantera. När ett designalternativ ska utvärderas är det inte säkert att det är bestämt vilka produkter som ska användas, tillverkare, typ av installationer, användarmönster och monteringsmetoder. Att genomföra LCA och LCC under sådana förutsättningar kommer naturligtvis medföra större osäkerheter i resultaten är för produkter med bestämda system och förutsättningar.

Arbetet som beskrivs i den här avhandlingen består av flera studier där metoder och procedurer har utvecklats för att underlätta att utvärdera designalternativ för byggnader med hjälp av livscykelverktyg. Effekt- och konsekvensutvärderingsmetoden

(ECE) beskriver hur tekniska systemgränser kan skapas på ett konsekvent sätt. Den fokuserar på hur sekundära effekter som uppkommer i andra delar av byggnaden än den som utvärderas ska hanteras. I en fallstudie visades att sekundära effekter kan ha betydande påverkan på resultaten. Även besluts- och valproceduren (DCP) utvecklades inom projektet. Den skapar förutsättningar att hantera valalternativ på ett strukturerat sätt när livscykelverktyg används för att ta fram beslutsunderlag. En annan fråga som studerats var hur pålitligt underlag kan skapas för inbyggda material och produkter. En process i vilken entreprenörerna på byggarbetsplatsen rapporterade materialdata i ett formulär utforskades för en kontorsbyggnad. För att demonsterara hur de utvecklade metoderna ska tillämpas utfördes flera fallstudier. Fyra fallstudier utvärderar de enskilda frågorna mer i detalj var för sig och ytterligare en visar hur man kan kombinera metoderna i LCA och LCC genom att optimera isolertjocklek för en byggnad.

Tyngdpunkten i arbetet har varit träffsäkerhet i resultaten snarare än förenklingar för att motverka felaktiga slutsatser kring vilka designalternativ som har låg miljöpåverkan och låga kostnader. Även om en viss förenkling erhålls genom att visa en mer strukturerad och konsekvent process för att hantera systemgränser och osäkerheter via designoptimering. Tillämpning av tillvägagångssättet som beskrivs i detta arbete kommer sannolikt att medföra slutsatser krig design med högre kvalitet samtidigt som det sparar tid och arbete vid genomförandet.

Abbreviations Used in the Thesis

AP	Acidification potential
DCP	Decision choices procedure
ECE	Effect and consequences evaluation
EP	Eutrophication potential
EPD	Environmental product declaration
GWP	Global warming potential
HRV	Heat recovery ventilation
LCA	Life cycle assessment
LCC	Life cycle cost
LCCA	Life cycle cost analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
NPV	Net present value
ODP	Ozone depletion potential
PCR	Product category rule
POCP	Photochemical oxidant creation potential
PV	Present value

1. Introduction

1.1. Background

For many years, the building sector has focused on making buildings more sustainable. In this respect, operational energy use has been considered especially important from an environmental perspective. However, the building and construction sector still accounted for 39% of energy and process-related carbon dioxide emissions in 2018 and global emissions from buildings increased 2% for the second consecutive year [1]. To mitigate this worrying trend, we must find building design solutions that minimise the climate impact of buildings. To reduce a building's energy requirements, more insulation and installations, like ventilation heat recovery, are being installed in the buildings, which are causing increased emissions generated by production and higher costs in the production phase. In recent years, there has been a growing awareness of the environmental impact from the value chain of the building sector and there are studies showing that the emissions from the production and operational phases of low-energy buildings are comparable in magnitude [2]. This means that finding solutions with the lowest total emissions at a reasonable cost, including both the production and operational phases, demands consideration of the entire life cycle of buildings.

Using simplified environmental analyses that consider a selection of environmental aspects, such as waste management and toxic compounds in the construction materials, does not fully capture the complexity of emissions and costs associated with a building's entire life cycle. More refined methods are needed that objectively compare different design options to optimise buildings with regard to environmental impact and cost for the complete life cycle. Appropriate tools for considering these aspects are life cycle assessment (LCA) and life cycle cost analysis (LCCA) [3].

The idea behind LCA is to summarise all the emissions from a product, from raw material acquisition to final disposal, and to calculate the potential environmental effects of these emissions. In LCCA all costs generated during the life cycle are related to a present value (PV), which makes it possible to compare future costs with present ones. For several decades, LCA and LCCA of buildings have been researched. In the 1980s, [4] developed a mathematical model, optimal energy retrofit advisory (OPERA), that addresses energy retrofits and how the strategy can be optimised for the life cycle cost (LCC) of a building.[5] evaluated seven designs of concrete and steel building frames using LCA. These are some early examples of LCCA and LCA applied to buildings with the aim of determining the design with the least environmental impact and lowest cost.

At the beginning of the millennium, the building sector started to utilise LCCA to compare energy improvement measures, and several tools were developed to ease the use of such analyses in building projects. Recently, LCA has also been implemented in the building sector, and environmental product declarations (EPDs) based on LCA are being developed which facilitates performing an LCA for entire buildings.

In [6] is an overview of the literature on LCA, life cycle energy analysis and LCCA for the building sector. They stress that although LCA is a mature method for simple products and materials, buildings pose new challenges. Reasons include:

- Buildings are site-specific and local environmental impacts might need to be considered.
- Buildings consist of many products with their own life cycles, making the data collection and simulation difficult.
- Buildings have long lives, due to their long operational phase. This leads to major uncertainties in the modelled scenarios.
- Design choices might affect the indoor environment, behaviour and performance during the operational phase. Typical LCA methodologies do not address these impacts even though they might contribute most to the total impact.
- The use of recycled materials in buildings is encouraged, and such data are usually not included in LCA databases.

[6] also states that it is difficult to compare different case studies since conditions like climate, location and building type are not the same. The scope (materials only or the entire building) is one parameter that leads to the high variation in the investigated studies, which in turn affects the system boundaries. Other important parameters that differ are lifetime considerations, functional unit, building typology and location.

There are several studies available that assess whole buildings over their entire life cycle, e.g., [7], [8], [2], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21] and [22]. Most previous studies concern residential housing but a few address office buildings. The documentation of buildings is often extensive and divided in such a way that each profession only needs to manage documentation relevant to their field. Additionally, building materials and products might not be explicitly specified. Instead a described function is fulfilled with an appropriate product and sufficient amount of this product. Although many previous studies are ambitious and thorough, the usual approach is to estimate the amount of materials and products based on architectural drawings and to confer with experts. This approach poses a risk of overlooking products and services with a large environmental impact, especially for more complex buildings such as larger offices.

LCA and LCCA have been combined in several optimisation studies. A global methodology to optimise concepts for extremely low energy dwellings, taking into account energy use, environmental impact and financial costs over the life cycle of the buildings is described in [23]. This study is divided into three parts: optimisation, LCI and LCCA. It focuses on energy efficiency measures in residential buildings by comparing different design options with a Belgian reference building. To perform the optimisation, a genetic algorithm was used with Pareto optimisation. A genetic algorithm approach was chosen due to the complex nature of buildings and the large number of parameters involved. Although methods using the genetic algorithm enable a fully automated process by setting up extra constraints, this would lead to increased complexity of the calculation functions. Hence, the outcome of the calculations had to be checked manually to make sure that the suggested design solutions were realistic. An example of inconsistencies presented in the article was the insulation homogeneity of the building envelope. Since the algorithm considered the building as a whole, it did not compare the different envelope components. Incorporated restrictions on maximal U-values were absent, as this would have increased the complexity of the algorithm too much. Therefore, a solution with 2 cm roof insulation and 20 cm façade insulation was found optimal in the simulations but is not realistic to actually carry out. Using Pareto-optimal solutions is preferable when dealing with optimisation problems that have multiple objectives, and the method results in several different optimised solutions that can be further considered in a decision process in which different target groups have various project goals [23].

To minimise the LCC and CO_2 equivalent emissions (all compounds normalised against the environmental impact of CO_2) from buildings, [24] uses a harmony search algorithm. They state that optimisation methods usually have difficulty processing discrete numbers, which might lead to optimum values that are not feasible to use in a real building. To manage this, only construction with combinations of products available on the market were used in the optimisation. [3] describes an approach to conducting life cycle sustainability assessments for refurbishing buildings. In this method the possible solutions were not calculated from continuous values; the authors argued that the measures to be evaluated should be identified by experts to filter out unrealistic options from the beginning, although they concluded that this might exclude some good solutions from consideration. In [25] a genetic algorithm and neural networks were combined in the same method, as the genetic algorithm was used to adjust the weights in an artificial neural network. The network was then utilised to optimise the external wall and windows for an office building with regard to several environmental impact categories. As computers become more powerful, it is possible to make more, performance-demanding simulations within a reasonable timeframe. This is reflected in later life cycle optimisation studies, such as [26], [27],

[28], [29], [30], [31], [32] and [33] as more design alternatives, parameters and target objectives are considered in the simulations.

In many cases, a change in the building's design will affect building parts beyond the change made. Such effects are referred to as secondary effects. An example of a secondary effect is when more insulation is applied in the external wall, and the floors and roof have to be elongated to support the increased wall thickness. The wider floors and roof are a consequence of, and not directly included in, the design change. Hence, they need to be considered in the comparison between different design options. Previous studies provide useful new procedures on the environmental and cost optimisation of buildings but do not fully address secondary effects or uncertainties present in early design evaluation. As a result, conclusions can be drawn based on misleading results if the methods are applied without including secondary effects or do not consider the uncertainties of the study design and the results.

Buildings are complex systems with many functions, products and stakeholders; therefore, a holistic approach is necessary when evaluating the building design. The building design process is commonly performed by a team of specialists with specific areas of expertise, for example architects, engineers and environmental specialists. They provide information and solutions within their own field for each design option in a building, but usually only have rudimentary knowledge of the other fields. This means it is difficult to appraise the extent of measures to be taken when a change that spans several fields is implemented. Ultimately, there is a risk that important secondary effects are overlooked when different parts are examined individually.

Buildings consist of many products and materials and have long use phases. When using life cycle studies to compare design alternatives for buildings, this poses a problem, as many uncertainties arise during the analysis. Although there is an awareness that LCA and LCCA provide results that are uncertain, many studies present their results as point estimates [34]. These uncertainties must also be considered to get reliable results and information from the calculations that can serve as valuable decision-support tools and assist decision-makers in choosing the final design.

As life cycle studies become more common in the building industry, there is an increased need for simpler methods to allow for more – and more accurate – assessments using fewer resources. It is important to realise how these simplifications affect accuracy and precision. Accuracy describes how close the assumed or calculated value is to the true value, and precision is a measure of the range of values. High precision means a narrow range with a point value as the extreme, while low precision means that the data have a long range of possible values. In studying a system, it is relevant to consider accuracy and precision for both input data and output data. Simpler models with fewer parameters and point estimates of input data will provide resulting values with less effort than would a more complex model but with less accuracy. At the same time, the total number of parameter uncertainties can become fewer due to fewer parameters, thus increasing precision. However, since a simple model decreases accuracy, it might lead to wrong decisions about which option has the lowest environmental impact. These kinds of simpler models will thus give misleading results "*…in which precision hides ignorance*" [35]. Although it is desirable to have input and output data with both high accuracy and high precision, of course, this is usually unattainable due to limited resources. Nonetheless, to obtain realistic results that provide reliable decision support, it is beneficial to strive for high output accuracy and to focus less on precision. It would therefore be useful to identify as many uncertainties as possible and carefully consider how the simulation model is affected by the implemented simplifications in order to be able to achieve high accuracy. It may not be feasible to evaluate all possible alternatives satisfactorily with the available resources in a project. The current design under consideration is usually explored in more detail than alternative designs. Since unknown emissions and costs in general are omitted in LCA and LCCA, this can make alternative designs appear more favourable than they are in life cycle studies, as stated by [36]:

> "*Generally, missing information in LCIs is implicitly set to zero. Errors introduced by such omissions cause a systematic bias towards lower values. Ignorance is thereby rewarded: a comparison between a well-documented process and its less completely analyzed counterpart will be biased towards favoring the latter – a very undesirable result of an LCI.*"

Early in the design phase and well into the construction phase, the exact type of product or material to be used in the building, as well as technical solutions such as heating, ventilation and air conditioning (HVAC), may still not be decided. Often there are several products and systems with suitable properties, but their material composition and production methods vary. Even if a decision is taken to use a particular product type, there can be several product suppliers, as well as different on-site assembly methods, that result in different emissions and costs. Additionally, the exact amount of material that is needed, the produced spillage and waste at the construction site might be unknown. Since the materials used in the building can be large contributors to the resulting emissions and costs of the building during its life cycle, these uncertainties are important to consider.

There are numerous research studies that suggest methods to manage uncertainties, with examples of stochastic uncertainties in the LCA and LCCA of building design and building products, e.g., [37], [38], [39], [40], [41] and [42]. Many of these studies focus on how to calculate parametric uncertainties once they have been identified and how to take them into consideration when evaluating the results. This is also what is generally referred to when discussing uncertainties in life cycle studies [43]. There are therefore several methods described in the literature on how to manage stochastic uncertainty, of which Monte Carlo simulation, Taylor series expansion and fuzzy variables are frequently occurring. These methods are described and compared in [44]. However, there are also other types of uncertainty to consider in life cycle studies of building design. Section 2 provides an overview of the uncertainties, defines different types of uncertainties and classifies them in Table 1. This topology is used when presenting and discussing uncertainties in this thesis. Many of the uncertainties in life cycle studies are of a different nature than stochastic uncertainty in the available data and are instead related to choices, e.g., decision criteria, design choices, modelling choices and system boundaries. Depending on which option is selected in each choice, different results can be obtained [45], [46]. To our knowledge, no studies have been conducted that describe a method to highlight the options for choices to make in life cycle studies in a consistent manner. Integrating uncertainty analyses into life cycle studies can have an effect on the model structure and approach, compared to a deterministic study. When carrying out LCA and LCCA as design decision support tools and taking into account possible uncertainties, it is necessary to reflect and likely alter the design of the studies and simulation models used in the calculations. This in turn affects how the results are presented and which conclusions are drawn from the results. Paper I, II, III and IV investigate specific parts of life cycle studies in detail.

The problems with LCA for buildings, described by [6] above, were discussed in the project work group, and the problem of how to set up the system boundary to compare design options was deemed especially important to examine further. In Paper I, a methodology was developed to mitigate the risk of overlooking important secondary effects when individually examining different parts. Paper II investigates how to compare different design options in the building design phase with regard to the environmental impact and cost. It focuses on the identification of secondary effects, and how to consider these in optimisation studies of building design with regard to environmental impact and cost. To do so, LCA and LCCA were implemented in a parametric case study of insulation thickness in an apartment building.

To investigate the issues of data collection and the risk of overlooking materials and products, a post-construction study was conducted that is described in Paper III. The study aims to determine the major environmental impacts of an office building by letting the involved contractors gather site-specific data on the investigated building to mitigate the risk of omitting important environmental factors of the life cycle. The approach involved conducting a case study in which an actual building was closely followed in real time, from the design phase until completion, and then the calculation was made on the finished building. This resulted in high-precision data on how the building was constructed, in contrast to assumptions that would have been used if the LCA was performed during the design stage. Paper IV presents and evaluates a procedure to manage choice uncertainties together with stochastic uncertainties to make a more informed and efficient decision regarding building design. The study addressed two issues: how to decide between design options when uncertainties are considered, and how to structure and present available choices in life cycle studies.

The work presented in Paper V describes how the developed methods are implemented in a case study, and therefore complements this thesis in summarising the doctoral research.

1.2. Aim and Objectives

The overall aim of this thesis was to develop a method to facilitate using life cycle studies as decision support for building design. The main objectives, addressed in five papers, were as follows:

- How to manage secondary effects when establishing technical system boundaries. (Paper I)
- How to make optimisations of building design considering the life cycle perspective of the building. (Paper II)
- How to manage uncertainties in life cycle studies and make informed design decisions. (Paper IV)
- How to manage uncertainties in life cycle studies regarding optimisation of building design. (Paper V)
- Collecting life cycle building data. (Paper III)

1.3. Scope and Limitations

The study explored how to facilitate using life cycle studies as decision support in the design of new buildings. This was done by investigating and providing methods and routines to manage specific uncertainties in the LCA and LCCA of buildings where there are identified knowledge gaps. Issues more directed towards the LCA and LCCA methodologies in general, such as allocation, data quality, impact factors, end of life scenarios and carbon storage, were not addressed. The study did not consider pure refurbishment projects and only included stand-alone single buildings. The study specifically looked at:

- Establishing the technical system boundaries.
- How to set up decision criteria and compare them with numerical results.
- Managing both stochastic uncertainties and choice uncertainties together.
- Optimisation of building design regarding environmental parameters and costs.
- Product and material life cycle inventory data collection in building projects.

When conducting life cycle studies of buildings, there are numerous uncertainties that will affect the numerical results, e.g., user behaviour, material properties, production variations, choice of future energy mix, maintenance policies, local climate, climate change and data gaps. The aim of this study was not to examine all possible uncertainties that might arise in these kinds of projects. Adding more choice or stochastic uncertainties might affect the conclusions in the case studies but not the demonstrated approach, which was the purpose of the case studies. To keep the study concise and focused on the issue at hand, it focuses on the uncertainties that are likely to have the largest impact on the results.

1.4. Thesis Structure

This thesis is based on the papers listed in the Publications section and refers to them in the text by their Roman numerals. The papers are appended at the end of the thesis. The thesis is structured as follows:

- Section 1 provides a background of previous research and a brief overview of the conducted research.
- Section 2 provides the theoretical framework for the methods used.
- Section 3 describes the methodology used to obtain the results.
- Section 4 presents the main results from the studies.
- Section 5 discusses how the results answer to the aim and objectives of the study and how they relate to and complement previous research.
- Section 6 presents the main conclusions.
- Section 7 presents topics that were identified as the potential focus of future research.

To keep the thesis focused and concise, the new calculations made that summarised the material from the other papers created in this project were compiled into Paper V. This paper therefore summarises and adopts the key findings of the other papers and can be considered an application of the complete method on a case. It is recommended to read Paper V together with this thesis to get a more complete view of the entire study.

2. Theoretical Framework

The concept of LCA began to emerge in the 1970s, mainly as an evaluation of different options for packaging. In 1997, LCA became a standardised procedure described in standards ISO 14040-43, which were later replaced by ISO 14040:2006 and ISO 14044:2006 [47], [48]. The standards provide a framework for conducting LCA but do not provide details for every given situation. Reality is complex, and the LCA practitioner often faces many different choices and assumptions that can affect the final results. Nonetheless, LCA is a powerful tool that aims to evaluate systems as close to reality as possible, albeit demanding in terms of time and resources. LCA is divided into the following four main parts [49]:

- Goal and scope definition
- Life cycle inventory (LCI)
- Life cycle impact assessment (LCIA)
- Interpretation

A method for performing an LCCA is described in standard ISO 15686 [50]. The net present value (NPV) is the sum of all considered costs calculated as a present value (PV). NPV is sometimes also referred to as global cost. The idea behind LCCA is that costs occurring in the future are discounted, compared to the costs incurred today. The reason is that money available can now be invested or deposited elsewhere, like in a bank or in stocks.

The outcomes of both LCA and LCCA depend very much on the input data, assumptions made and methodological choices. The choices in goal and scope, parameter and input values as well as assumptions on lifetime, maintenance requirements, future energy systems, etc. have a great impact on the results and will in turn impact the decisions taken.

There are many ways to classify types of uncertainties in an LCA. [51] defines them as:

- Parameter uncertainty (e.g., empirical inaccuracy, unrepresentative and lack of data)
- Model uncertainty
- Uncertainty due to choices

- Spatial variability
- Temporal variability
- Variability between objects/sources.

[52] provides an overview of LCA uncertainties and methods to manage these uncertainties, adding three types of uncertainties:

- Epistemological uncertainty caused by lack of knowledge on system behaviour
- Mistakes
- Estimation of all types of uncertainty, which in itself is a source of uncertainty.

An additional type of uncertainty was added to the list by [43] – relevance uncertainty (e.g. environmental relevance, accuracy or representativeness of an indicator towards an area of protection). [43] also states that a common way to classify uncertainties is: parameter, model, and scenario uncertainty, and that most of the above uncertainty types are subclasses of the last three types. In [53] types of uncertainties are instead grouped as:

- Stochastic uncertainty
- Choice uncertainty
- Lack of knowledge of the studied system.

The main difference between stochastic and choice uncertainties is that choice uncertainties have several relevant options available, but no values in between the options. Stochastic uncertainty can be represented by, e.g., possibility distributions and is closely related to parameter uncertainty, as variability and data gaps can be managed by stochastic methods.

In [54] and [55] an extensive literature study was carried out and used to categorise uncertainties in infrastructure projects and map available methods to manage each type of uncertainty. The focus of the articles was uncertainties for LCC, but the results were largely based on research from the LCA community, as the authors state that the subject of uncertainties was treated to a larger extent in research related to LCA rather than LCC. The results are therefore highly relevant for LCA as well. Several possible ways of categorising uncertainties are discussed in [54] and [55], and two types of categorisations are used in their studies. One is divided into the groups of parameter, model and scenario uncertainties (PMS), and the other classified into aleatoric and epistemic uncertainties.

Model uncertainties can be classified under other types of uncertainties, such as choice uncertainty (e.g. LCI modelling principles) or stochastic uncertainty (e.g. derivation of characterisation factors). It is useful to separate them to understand to what extent the total uncertainty of the LCA is influenced by inventory data or modelling uncertainty. In [54] model uncertainties are divided into seven subcategories: model structure, approximation in computer coding, extrapolation errors, and four types of simplifications (averaging, reduced observations, reduced variables and functional form).

When referring to scenario uncertainties there are several different definitions mentioned in the literature. In [53] and [56] a scenario is described as choices to be made about the future and [53] points out that only the options chosen are possible, while options in between these choices should not be considered. According to [57] a scenario in LCA can be defined as "*...a description of a possible future situation relevant for specific LCA applications, based on specific assumptions about the future, and (when relevant) also including the presentation of the development from the present to the future.*" [58] agrees that there is a time aspect for scenarios, but that includes the past, the present and the future. Regarding the aspect of considering options in between chosen scenarios [58] disagrees with [53] and states that these paths can also be dealt with in scenario analyses. In [54] scenario uncertainty is simply defined as the choices of a researcher that lead to uncertainty. Though there does not seem to be consensus on what a scenario in LCA and LCC refers to, most identified sources seem to regard a scenario as a set of values to use in calculations when there is at least one choice (with several options) to be made in the study.

To avoid confusion among the different typologies used in the literature, the project established a new typology of uncertainties deemed suitable for life cycle studies of buildings based on the identified research, as presented in Table 1.

Table 1. Classification of uncertainties.

Stochastic uncertainty. Numerical range of values with a probability distribution.	**Parameter uncertainty**. E.g., empirical inaccuracy, unrepresentative data and lack of data.	
	Stochastic model uncertainty. E.g., derivation of characterisation factors.	
	Variability. Different possible values depending on the circumstances.	**Variability between objects/sources**. E.g., materials that have many different producers.
		Spatial variability. E.g., emissions can have different impact depending on local conditions.
		Temporal variability. E.g., electricity production that differs over the year.
Choice uncertainty. When there is more than one option to choose from.	**Choices regarding the studied system**. E.g., system and building design choices.	
	Model choices. Which calculation methods and assumptions are to be made, e.g., allocation, recycling, extrapolation.	
Scenario uncertainty. A combination of all (future) values and choices selected in the study.		
Epistemological uncertainty. Lack of knowledge.		
Mistakes. E.g., calculation errors, wrong input.		
Estimation of uncertainty. Assumptions regarding identification and magnitude of uncertainties.		
Relevance uncertainty. E.g., environmental relevance, accuracy or representativeness of an indicator towards an area of protection.		

Table 2 contains an overview of uncertainties that were identified in the literature and experience from the Swedish building industry, which should be considered when conducting life cycle studies to be used as a decision support tool for building design.

Table 2. Overview of important uncertainties to consider in life cycle studies of buildings.

Part of life cycle study	Uncertainty
Goal and scope	Formulation of the question
	Formulation of distinct decision rules
	Confidence level
	System scenario
	Functional unit
	Technical system boundaries
	Cut-off rules
Calculation assumptions	Type of service life of building
	Length of service life of building
	Use and management
	Maintenance, replacement and refurbishment intervals
	Periodisation
Life cycle inventory	Specification of building materials and products
	Performance of building materials and products
	Service life of building materials and products
	Costs of products and materials
	Stratification and allocation of costs
	Local climate
	Energy performance of building
	Energy sources
	User patterns
	Transportation
	Services
	External factors

It would be beneficial if the uncertainties could be grouped together according to type and the phase in the building life cycle in which they appear. Classification of uncertainties in LCAs is useful as different types of uncertainties need to be managed or reduced in different ways [51]. For example, if model uncertainties need to be mitigated, software or a method that can manage the necessary uncertainties needs to be chosen. If, instead, large uncertainties are caused by parameter uncertainties, it may be necessary to collect more data to increase the accuracy. However, this thesis found that the categorisation of an uncertainty will depend on the choice of model used to manage the uncertainty. If, e.g., the type of material to be used in construction is not decided, it can be managed in several ways. One model choice is to use an average or median value for the materials that could be used. The uncertainty will then be a point estimate of a parameter type. Alternatively, it is possible to choose one or more suitable materials and use the values for each choice in the calculations. The uncertainty is then a choice type. Another option is to treat it as a stochastic uncertainty by constructing a distribution of possible values for the materials and use probabilistic methods to calculate the uncertainty in the results. It is also possible to combine the different methods, e.g., by grouping the materials depending on certain characteristics and use the probability distribution or expected value for each group. Depending on how the life cycle study is designed and how the different uncertainties are defined, the uncertainties can appear in different parts of the building life cycle. It is therefore difficult to make a generalised categorisation of the uncertainties with regard to the building life cycle. A similar conclusion was reached in [55].

3. Methodology

The working procedure was a combination of inductive analysis together with quantitative elements such as calculations and simulations. The project was conducted in close collaboration with representatives from the building industry and focused on addressing issues the industry needs to improve. This was done by brainstorming with the industry partners in the beginning of the project and at regular intervals when new information was found. It was then investigated if there were proper solutions in previous research by reviewing research literature. Issues that were found to have satisfactory solutions were set aside, and research gaps were investigated more in depth. This was done through analytical reasoning to find an approach that seemed promising. To evaluate and concretise the analytical reasonings, they were carried out in case studies. This might make the solutions more case specific but mitigate the risk of overlooking critical details or include unnecessary precautions. To facilitate solutions that are feasible in practice, evaluations and revisions were made in consultation with the industry partners.

The inductive analyses were carried out in Paper I and IV in order to develop the Effect and Consequences Evaluation (ECE) method and Decision Choices Procedure (DCP). The analyses were complemented with discussions and informal interviews with industry stakeholders. We started with an iterative process in which different approaches for implementations were discussed with the stakeholders involved in the research project. Between meetings the conclusions from the stakeholder meetings were used to investigate the state of the art through literature studies and contact with external stakeholders (not included in the project) in the building sector who contributed detailed knowledge of design procedures and the challenges of early decisions. This raised further issues to be taken into account in the development of methods and routines. This resulted in new approaches or modifications of existing ones. The ECE method and DCP were then evaluated separately in quantitative case studies with numerical simulations and calculations in Paper I, II and IV. In Paper V a quantitative case study was carried out in order to demonstrate how the results from Paper I, II and IV could be combined with common simulation procedures to manage secondary effects as well as choice and parameter uncertainties in a single approach. The ECE method consists of the steps described in Table 3.

Table 3. Description of the ECE method.

Step	Description
1	Clearly describe the design option to apply.
2	Decide a suitable functional unit for the affected system under evaluation, not just for the life cycle of the design option.
3	Identify the likely effects of the design option itself.
4	Determine the consequences each effect might have on the system. By consequences, we mean adjustments that have to be made both inside and outside the actual design option's life cycle.
5	Similar to step 3, identify the likely effects of the identified consequences themselves.
6	Similar to step 4, evaluate the additionally consequences each effect of the identified consequences might have on the system.
7	Repeat steps 5 and 6 until no more effects and consequences can be identified.
8	The possible system boundary is then obtained by describing the design option and all the consequences as unit processes, including their dependencies on each other.
9	Calculate the magnitude of the impact for each effect in every unit process and decide whether or not to include the process by comparing it to the goal and scope of the study.
10	Group the processes into foreground and background systems.

By following the ECE method, a system boundary that considers the secondary effects could be established. This was used to evaluate the importance of secondary effects in Paper I and II and was included in the complete approach in Paper V. The DCP was used to highlight and evaluate different choices and their options in Paper IV and V. The procedure consists of the steps in Table 4.

In the case studies the entire life cycle of the buildings was considered based on the standards ISO 14040:2006 [47], ISO 14044:2006 [48] and ISO 15686 [50]. This avoided suboptimal design solutions that merely shift the cost or environmental impact to life cycle phases not considered. In the building industry, the life cycle perspective largely centres around EN 15804 [59] with the life cycle divided into several phases. To facilitate the application of the results from this study, the same structure of the life cycle was adopted. Since there is currently a sharp focus on global warming and cost, GWP and LCC were chosen as the target objectives to minimise in the case studies for Paper I, II and V. In Paper III and IV, the stakeholders showed an interest in providing a broader environmental perspective, so the impact categories prescribed in EN 15804 were instead considered. These impact categories are GWP, eutrophication potential (EP), acidification potential (AP), stratospheric ozone depletion potential (ODP) and photochemical oxidant creation potential (POCP).

Table 4. Description of the DCP.

Step	Description
1	Identify the choice preferences and decision criteria to ensure that the decisions taken are in line with stakeholder expectations.
2	Map out a choice palette or a decision tree on order to get an understanding of the problem's complexity.
3	Present and discuss the choice palette or decision tree to show the complexity of the problem to the stakeholders.
4	Select and justify the chosen path to explain why the choices are preferred.
5	Calculate the results for the chosen combination or combinations.
6	Compare the calculated results against the decision criteria to obtain a design choice.

Two different buildings were studied in the project. A concept apartment building developed by Skanska AB, with some construction details altered in order to make it more representative of typical building practice in Sweden, was evaluated in Paper I, II and V. Since it was a concept building it did not have a set location, but in the study the assumed location was Gothenburg, Sweden. It had a rectangular floor layout with inside measurements of 16.5 m width, 17.1 m length and 2.5 m height, and contained six floors. The external wall consisted of steel stud frames and mineral wool insulation, and the intermediate floors consisted of hollow concrete core slabs. The roof had expanded polystyrene insulation with an insulation board and covering. The ground slab was made of reinforced concrete with expanded polystyrene insulation and a crushed stone base beneath. To reduce thermal bridges, the slab also had a layer of expanded polystyrene as perimeter insulation. A sketch of the construction is shown in Figure 1. The studied object in Paper III and IV was an office building developed by the Swedish company Vasakronan, in which seven of the floors were made mainly from concrete and two floors mainly from wood. The building was closely followed in real time from the design phase through to completion, and then the calculation was made on the finished building. More details regarding the materials used can be found in the supplementary file for Paper III (www.mdpi.com/1996-1073/12/13/2588/s1).

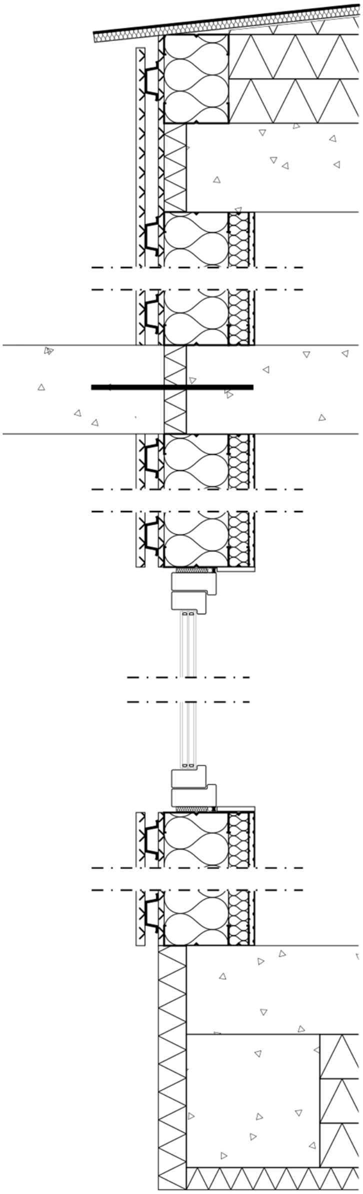


Figure 1. Sketch of the construction evaluated in Paper I, II and V.

The material amounts were acquired by measuring architectural drawings in Paper I, II and V. In Paper III and IV, the material amounts were provided by the on-site contractors based on purchased material and products in the project. Data regarding environmental impact were gathered from EPDs to get case-specific results. If no EPD existed for the investigated item, proxy data from EPDs of similar products were used instead. Byggvarubedömningen [60] and building declarations were used to find raw materials, content and production energy for built-in products. To calculate production energy when that information not available from other sources, the Ecoinvent database version 3.2 [61] for similar products was used with Simapro v8.0 [62], a life cycle assessment software program. Simapro was used to simplify the access to the Ecoinvent database that is an extensive database with global environmental information for products and materials. To obtain weight and construction costs a software named Sektionsdata [63] was used complemented with product safety data sheets containing information about product density and product information data sheets that often contain the mass per given unit (pcs, m^2, m, etc.). Sektionsdata was used since it has a digital library with cost and constitution of most constructions used in Sweden that are updated regularly.

The calculation procedure involved collecting data in a relational database file in the database management software Sqlite [64]. The data were transformed or aggregated to fit into software that performed the calculations and simulations. The results were then exported from the software into the database. The results could then be post-processed using scripts. This workflow with scripts takes more time than working directly in the simulation software but provides several advantages. Using a relational database makes it possible to connect simulation parameters with the results. This makes it faster and easier to repeat simulations with many changes to input parameters and evaluate how these changes affect the results. It also significantly reduces the time to change simulation files and the demands on storage space. Sqlite was chosen since it stores the database in a file, which makes it easier to access and move the database. Another big advantage of scripting is that the most suitable software for a specific task could be chosen. No software excels in all parts of a simulation procedure such as data management, calculations and results processing, especially when there are divergent target objectives such as cost and environmental impact. Instead of making compromises on such aspects, the database and scripts work as a proxy to take advantage of the software's strengths and support its weaknesses. Energy and power use during the operational phase were calculated using the simulation software EnergyPlus 8.2.7 [65] with the help of the software Therm 7.3 [66] and Heat 3 [67] to calculate thermal bridges. These software programs were chosen as they provide sufficient accuracy, and EnergyPlus is a transparent open-source calculation engine that facilitates import and export of data as well evaluation of results.

The LCC and environmental impact categories were calculated using self-made algorithms and the data collected as mentioned above. The main reason to not use existing software was to obtain sufficient transparency of the calculations to facilitate evaluation of the results. In Paper III, the data management and product calculations were to a large extent made by co-author Peñaloza. Since several persons were involved and everyone had previous experience of the spreadsheet software Microsoft Excel [68], it was used to manage data and perform calculations. In Paper I, II, IV and V, calculations were made mainly in Python [69] complemented by R [70]. Python is a multi-purpose programming language with strong support for numerical calculations and post-processing, while R is aimed more at statistical calculations.

4. Results

This section presents the main results of the studies from in the papers included in this thesis. The first study considered the ECE method described in Table 3, which was developed to manage secondary effects when the technical system boundary was established. It was therefore a result from the study as well as an applied method. In step 1 in the method, it is important to clearly describe the design option to apply. If the formulation is vague, it is difficult to foresee its consequences on other parts of the building. It will then depend on how the description is interpreted. Since adding secondary effects will enlarge the system under evaluation, the functional unit must properly reflect this larger system. This is considered in step 2 of the method. In steps 3-7 effects on the building caused by the design change are considered. Example of effects are changes in volume, surface area, weight, energy, power, cost, construction time, moisture risks, fire safety, indoor environment, acoustics, accessibility for people with disabilities, security and stormwater management. Starting with the design option, all relevant effects are identified. Possible consequences are considered for each effect. This procedure involving effects and consequences is then repeated until no more consequences and effects can be found. In steps 8-10, the identified consequences and their effects are then evaluated numerically to find out whether they fall below the cut-off criteria and be left out, or whether they should be included as a unit process in the system boundary. An example of the principle behind the ECE method is described in Figure 2.

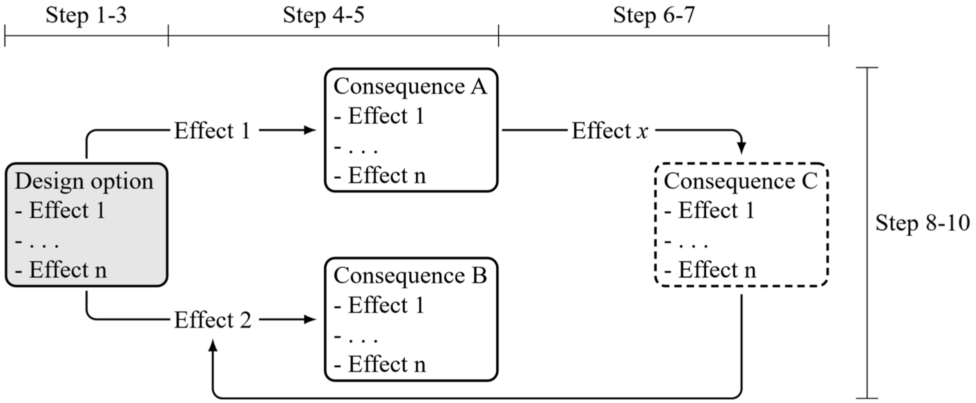


Figure 2. Principle of the ECE method. The design option is defined and its possible effects are identified. Effects 1 and 2 lead to consequences A and B, respectively, which in turn will have their own effects. Effect x *in Consequence A will result in Consequence C. In C there are no choices to be made (contrary to A and B) and it can be placed in the background system, which is indicated by the dashed frame. Effect 2 also occurs in C and will influence Consequence B. Note that Effect n appears in all processes, but it will not have any consequences.*

An example of a system boundary using the ECE method for adding wall insulation is illustrated in Figure 3. The system was obtained by carrying out steps 1-8, which means that it was before the magnitude of the effects in each unit process was calculated. The system in Figure 3 therefore shows unit processes that have a potential to affect the results before their impact on the results are evaluated. Further investigation showed that some processes had a small impact and could be omitted without affecting the conclusions. The significant unit processes and their numerical results are shown in Table 5.

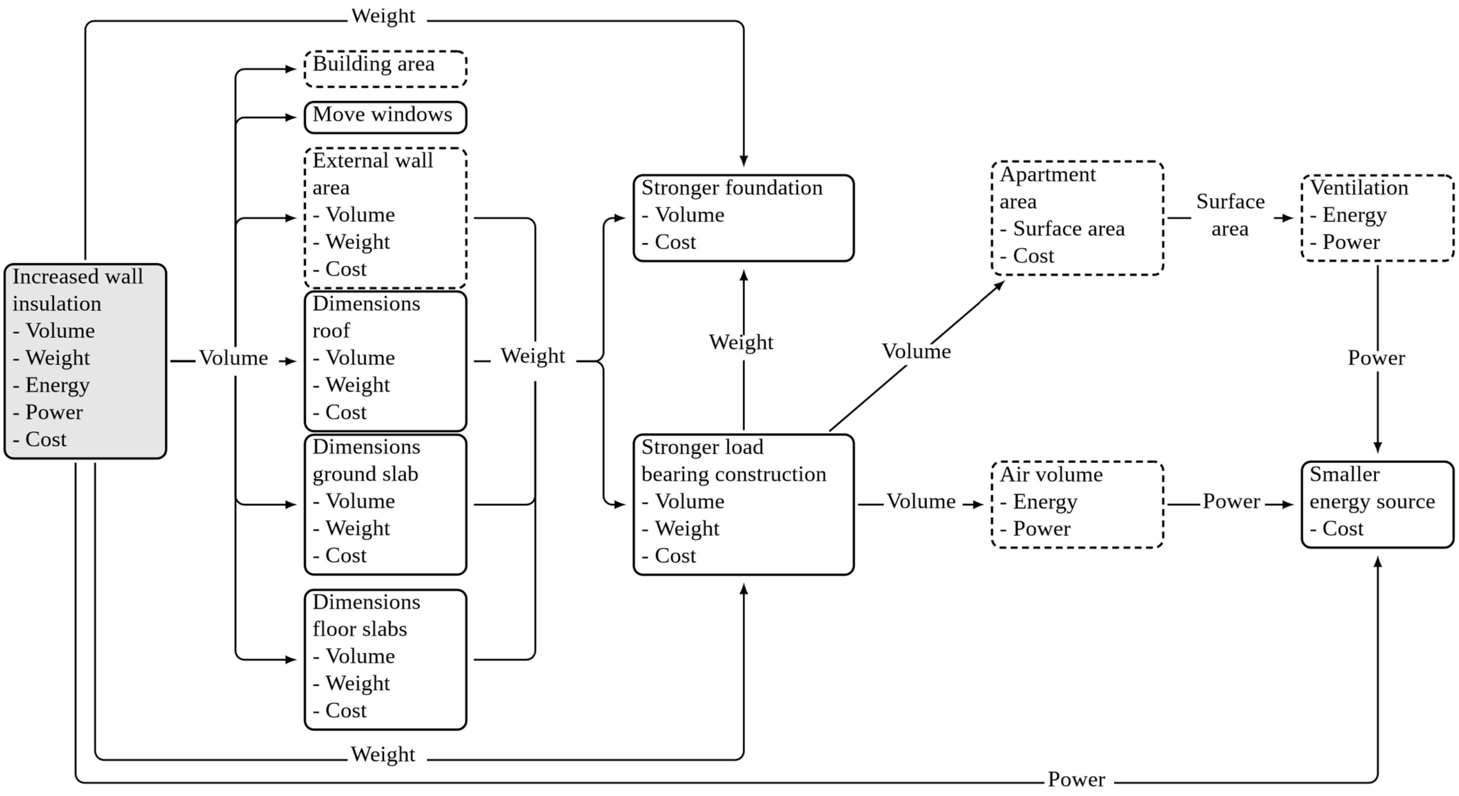


Figure 3. Example of a potential technical system boundary established by the ECE method in Paper I. The arrow labels identify the effect by naming the property that has been changed in the preceding process.

Table 5. The cost and environmental impact for each unit process.

Process		GWP (kg CO_2-eq/f.u.)	Net present value (SEK/f.u.)
Increased wall insulation			
	Material	18.2	738.3
	Energy	-31.0	-100.4
Dimensions, roof			
	Material	1.4	41.3
	Energy	0	0
Dimensions, ground slab			
	Material	1.3	29.5
	Energy	0	0
Dimensions, floor slabs			
	Material	4.8	118.1
	Energy	0	0
External wall area			
	Material	0.4	59.1
	Energy	0	0
Stronger load bearing construction			
	Material	*omitted*	*omitted*
	Energy	0	0
Smaller energy source			
	Material	0	0
	Energy	0	0
Sum			
	Material	26.2	986.4
	Energy	-31.0	-100.4
Total			
	Material + energy	-4.8	886.0

Often there are more complex design options with several alternatives that need to be evaluated in the design phase. Paper II demonstrated how to optimise building design considering the life cycle perspective of the building for more extensive design alternatives. The conducted case study presented different combinations of insulation thickness for the walls, roof and slab that were investigated for the same building as in Paper I. Figure 4 shows how the Pareto front was affected by the secondary effects. The simulation ID refers to insulation thickness in mm for walls (w), roof (r) and ground slab (s). If the secondary effects were omitted, the results showed lower GWP and LCC for many of the design options, which made them look more favourable than they really were with the secondary effects included.

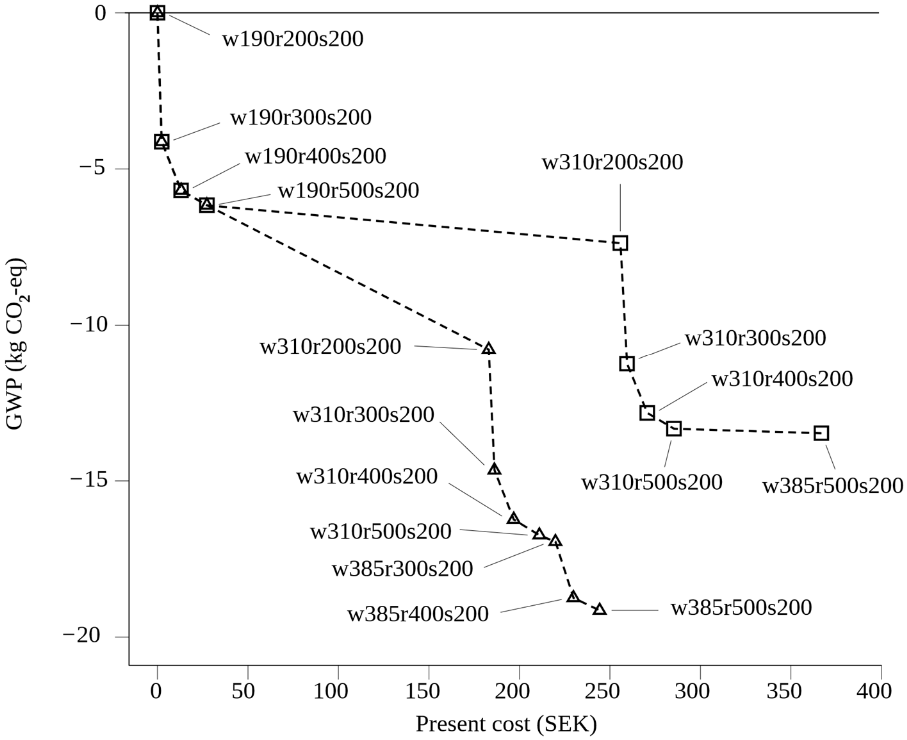
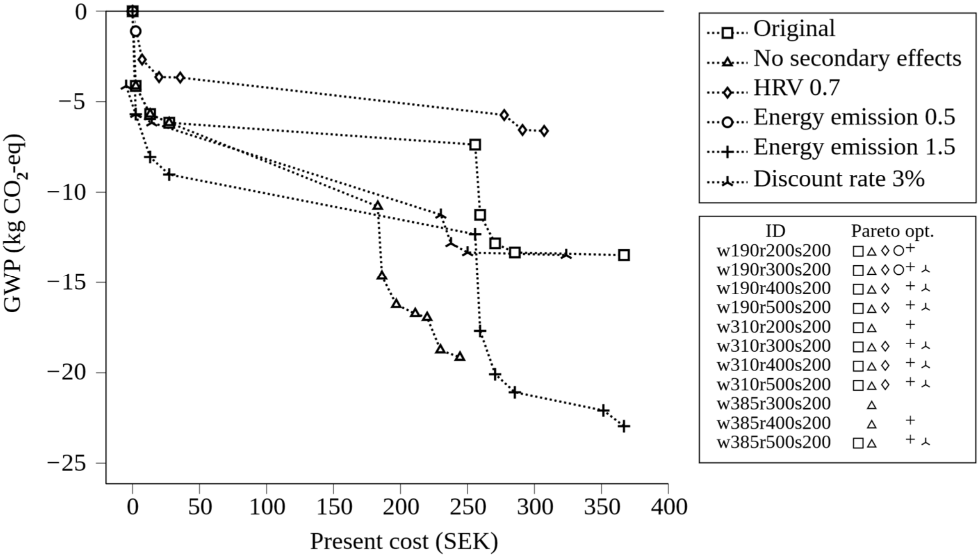


Figure 4. Pareto fronts from Paper II, with included secondary effects (squares) and excluded effects (triangles).

Decisions on optimal energy measures were not only affected by the secondary effects, but also depended on the prerequisites of the building and modelling choices. This is shown in Figure 5. Besides secondary effects, installation of a heat recovery ventilation (HRV) system, energy emissions and discount rate affected which ones were the Pareto-optimal design solutions. The heat recovery efficiency was assumed to be 0.7 and the emissions from energy were varied by multiplying the factors 0.5 (56 g CO_2-eq/kWh) and 1.5 (168 g CO_2-eq/kWh). The discount rate was lowered from 5% to 3%. These might be choices that need to be made at the time of the conducted evaluation of optimal insulation thickness.



ID	Pareto opt.
w190r200s200	□ △ ◊ ○ +
w190r300s200	□ △ ◊ ○ + ⅄
w190r400s200	□ △ ◊ + ⅄
w190r500s200	□ △ ◊ + ⅄
w310r200s200	□ △ +
w310r300s200	□ △ ◊ + ⅄
w310r400s200	□ △ ◊ + ⅄
w310r500s200	□ △ ◊ + ⅄
w385r300s200	△
w385r400s200	△ +
w385r500s200	□ △ + ⅄

Figure 5. Pareto solutions for the variations in the sensitivity analysis in Paper II. The solutions in the cluster to the upper left all have a wall insulation thickness of 190 mm. In general, solutions with more insulation are placed further down to the right for each variation of calculation parameter. The box below the legend shows the ID of the Pareto-optimal solution for each variation.

The emission factor and discount rate were examples of subjective choices that can influence the numerical results and conclusions regarding design solutions. To manage uncertainties in life cycle studies and take informed design decisions, the procedure Decision Choices Procedure (DCP) was developed. It is presented in Paper IV. Like the ECE method, it is both a result from the study and implemented in the methodology. The DCP considers and highlights the choices commonly present in life cycle studies. It will thereby facilitate decision-making regarding building design when subjective and stochastic uncertainties are considered, as described in the steps in Table 4. To get an overview of the choices and options, a choice palette was introduced to facilitate the implementation of DCP (see Table 6). The choice palette lists relevant choices and their options but does not describe the dependencies between the options.

Table 6. Example of a choice palette of the presented subjective choices in a study. It provides an overview of three choices to consider and the different options in each choice.

Choices to consider	Available options
1 Choice i	a b
2 Choice ii	a b c
3 Choice iii	a b

To manage uncertainties in life cycle studies regarding optimisation of building design, the ECE method and DCP were combined into a more general approach in Paper V. The approach was demonstrated as a case study to find Pareto-optimal solutions for the insulation of the building envelope in a multi-family building. It was based on the case study in Paper II, but it also addressed parameter and choice uncertainties. The choice palette for the study is shown in Table 7.

Table 7. Choice palette from the study in Paper V

Choices to consider		Available options						
1	Optimisation targets	a	b	c	d	e	f	g
2	Evaluation criteria	a	b					
3	Confidence level	a	b	c				
4	Outward or inward insulation	a	b					
5	Functional unit	a	b	c				
6	Periodisation	a	b					
7	Calculation period	a	b	c	d			
8	Discount rate	a	b	c				

The option set 1g|2b|3a|4b|5c|6a|7b|8b represents:

- 1g: The optimisation targets LCC and GWP together.
- 2b: The results for LCC and GWP are compared separately and Pareto-optimal design options are obtained.
- 3a: Point estimates are used in the data.
- 4b: The insulation is applied externally in the construction.
- 5c: The functional unit is 1 m^2A_{temp}, which complies with Swedish laws and regulations for the next 50 years.
- 6a: Periodisation is used for the environmental impact.
- 7b: The calculation period is 50 years.
- 8b: The discount rate is 5%.

The GWP and LCC for case 1g|2b|3a|4b|5c|6a|7b|8b can be seen in Figure 6. Out of the 64 combinations of different insulation thicknesses, nine were Pareto optimal. The insulation thicknesses are notated as letters for the construction parts wall (w), roof (r) and s (slab), followed by the thickness in millimetres.

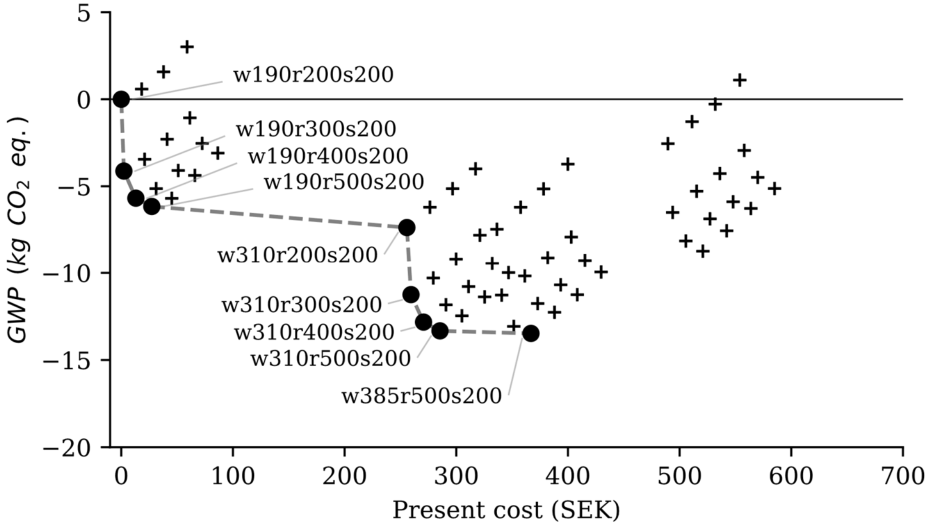


Figure 6. Global warming potential and life cycle cost for all simulated insulation combinations of the options 1g|2b|3a|4b|5c|6a|7b|8b. The circles indicate the Pareto-optimal solutions and the dashed lines indicate the Pareto front.

When parameter uncertainties were introduced in the data, the results were not single values but a range of possible values. The results could then, e.g., be described as confidence intervals with a chosen confidence level. Figure 7 shows the results when maintenance intervals, service lives, energy global warming potential and energy cost were assumed to have normal distributed values with standard deviations of 10%, and the results have a confidence level of 70%.

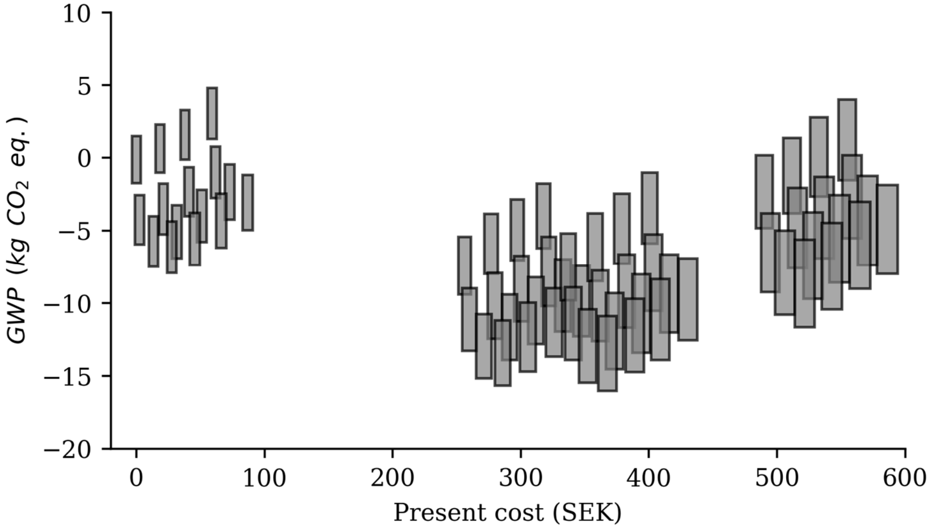


Figure 7. Global warming potential and cost for all 64 simulated insulation combinations of options 1g|2b|3c|4b|5c|6a|7b|8b. Maintenance intervals, service lives, energy global warming potential and energy cost were assumed to have normal distributed values with standard deviations of 10%.

Compared to point estimates, it is more difficult to discern a Pareto-optimal solution set for confidence intervals. The definition of Pareto-optimal solutions set used in this study was the set with only strictly non-dominated solutions. For confidence intervals, this was interpreted as follows. Design solutions for which another solution exists in which maximum values for both LCC and GWP are lower than the considered design are not Pareto optimal. For 1g|2b|3c|4b|5c|6a|7b|8b the Pareto-optimal set is illustrated in Figure 8.

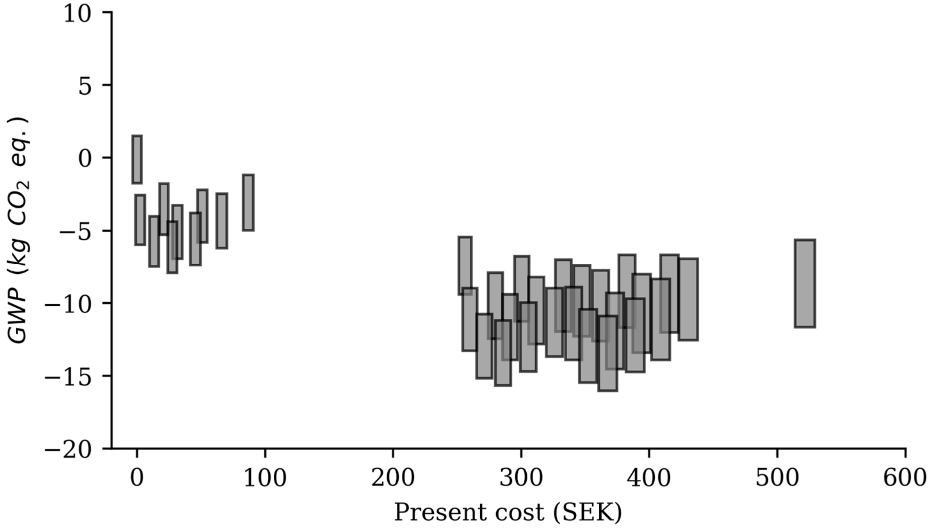


Figure 8. Pareto-optimal solutions regarding global warming potential and cost for the simulated insulation combinations of options 1g|2b|3c|4b|5c|6a|7b|8b.

A plot of the confidence intervals as in Figure 7 and Figure 8 provides some insights on the spread of the solution set, but does not indicate which are the promising solutions or how the solution set is affected by choices in the study. Table 8 in Appendix A shows how to compare the solution set for the alternatives:

- 1g|2b|3c|4b|5c|6a|7b|8b: Confidence level 70% (same as Figure 8).
- 1g|2b|3c|4b|5c|6a|7b|8a: Confidence level 70% and discount rate of 3%.
- 1g|2b|3c|4b|5c|6a|7b|8c: Confidence level 70% and discount rate of 7%.
- 1g|2b|3c|4b|5c|6a|7d|8a: Confidence level 70% and a reference calculation period of 100 years.

Materials and products omitted from design options can lead to results that underestimate environmental impact and costs. In Paper III, an LCA was conducted on the built-in materials and products to investigate and improve the collection of life cycle building data. The results clearly showed that the installations had a large share of the building's total environmental impact even if they represented a small amount of the total mass in the building. The environmental impact was 14–32% for the installations in four out of five environmental impact categories (see Figure 9). For GWP, the life cycle phase with the largest emissions, besides energy use during operation (B6), is the manufacture of building products (A1–A3), mainly due to the building framework and interior construction parts. The replacement (B4) of parts in the heating, ventilation and air conditioning (HVAC) system also has a relevant impact. The results for environmental impact categories EP and AP (acidification and eutrophication potential) showed less importance of the concrete framework in production than for GWP. The dominant processes concerning EP and AP were the production and replacement of copper pipes and other HVAC components. The results for the impact categories POCP and ODP showed that POCP was mainly affected by the production of the construction materials and products, especially the concrete framework in this case, mainly due to its content of expanded polystyrene insulation. ODP, on the other hand, was heavily affected by the energy use during operation of the building and had less impact from the material and building products compared to the other environmental impact categories investigated.

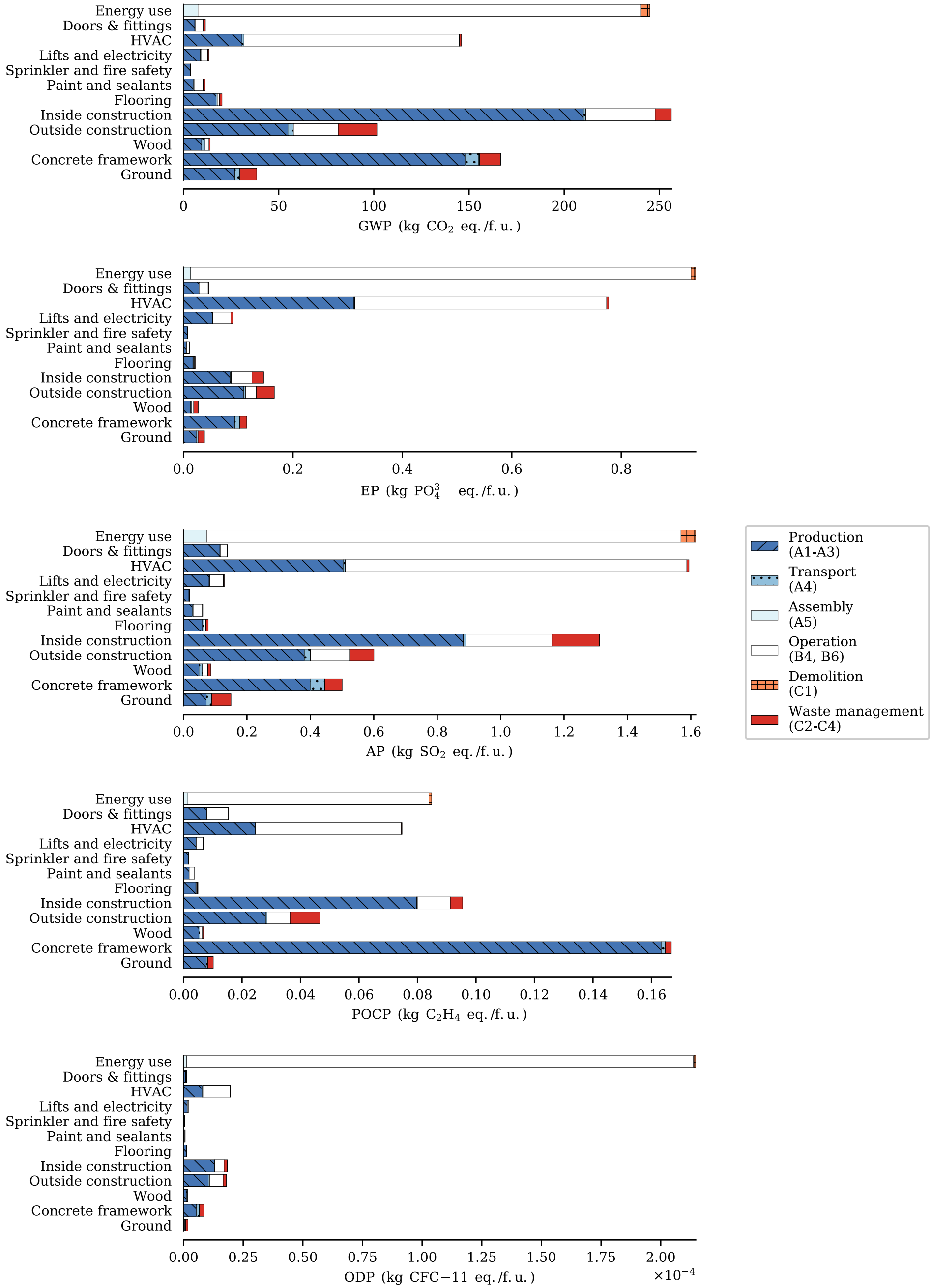


Figure 9. Impact of the different parts in the building for the environmental impact categories investigated in Paper III.

5. Discussion

The overarching goal of this study was to develop a method that practicing consultants can use to produce a reliable evaluation of building design alternatives regarding environmental aspects and costs. At the same time, the need of resources required to perform the evaluation should be low. The benefits of such a method are immense when designing buildings to decrease the environmental impact and costs, since this can be done at a large scale. However, life cycle studies quickly become complex as they aim to simulate the reality with many different aspects and scenarios. When incorporating uncertainties, the complexity increases even further. Developing a quick, simplified method that does not reflect this complexity is likely to suggest higher precision of the results than the available information provides. At the same time, the accuracy – how close the results are to the "true" value – is probably not addressed. Neglecting to take into account the lack of information in a study does not allow for a fair comparison between design alternatives, since it may benefit the alternative with less information. An analysis of such results might lead to faulty decisions with suboptimal designs. The aim of this thesis is therefore to provide a process that enables a fair comparison among building design options regarding environmental aspects and costs. The emphasis of the thesis is more on accuracy rather than on simplification in order to mitigate erroneous conclusions regarding the design's performance. However, some simplification of life cycle studies is achieved by providing a structured and more consistent way of managing technical system boundaries and uncertainties in design optimisation.

The main target group for the project is practitioners of LCA and LCCA in the building industry. Since LCA and LCCA represent a mature field of research, many issues found in the study were solved by examining previous research, such as data gaps and parameter uncertainties, as mentioned in the introduction. However, although there are several existing life cycle studies on buildings, it is difficult to find step-by-step methods that describe the entire process and reasoning around the steps. There are some examples of studies that describe the criteria of suitable system boundaries. [71] describes how to address the issue of system boundaries on a generic level for products by giving general guidelines and principles to be applied in any life cycle assessment. [72] further addresses how to reason when deciding on the boundaries in general for change-oriented life cycle inventories. However, there is no detailed description on the workflow to establish a system boundary that fulfils the described criteria. For experienced researchers this might be of less concern, since it is possible they have created their own solutions. On the other hand, this might be a large hurdle for less experienced practitioners. They do not have the time or resources to solve the kind of issues that were investigated in this study. For spreading the utilisation of life cycle studies in the building sector, there is a need to provide guidance on difficult issues but also put them into the context of a complete LCA or LCCA. This is addressed in this thesis by looking into specific issues that are identified in separate studies and then compiling the solutions into a single approach. In developing the approach, I also intended to make it feasible for an average practitioner of life cycle studies to use. A strategy for obtaining more practical solutions is to base the process on existing methods when available. Another is to make simplifications that are estimated to significantly reduce time and resources with an acceptable loss of quality. An example of the latter is introducing the choice palette as a compliment to a decision tree in the study described in Paper IV. Creating a decision tree when there are few alternatives is a minor task. However, as the number of choices and their options increase, the burden increases exponentially. Additionally, if new choices are realised and added late in the process, this can result in the need to revise much of the tree. For the choice palette each new choice is added with an additional row, which decreases the complexity compared with a design tree when there are many choices considered in the study.

The intended use of the suggested approach is to compare design alternatives for buildings. It might be less suitable when conducting LCA or LCCA to create a declaration or certificate such as an EPD. In these cases, it is more important to have a set procedure to ease comparison between different products or buildings. However, the suggested procedure can be used to evaluate how rules and procedures can affect the results and conclusions that can be made based on the declarations or certificates.

One aspect that the suggested approach considers is how to establish a relevant system boundary of the investigated design alternative. The importance of correctly establishing the technical boundaries became very clear in Paper I since lower GWP and LCC are estimated for many of the design options if secondary effects are not taken into account, which make them look more favourable than they are in reality. To my knowledge, the issue of the impact of secondary effects in buildings and how to manage them systematically has not been addressed in previous research. It is therefore difficult to appraise whether their impact on the results are large or small in general. Logically, more extreme design options will have a greater influence on secondary effects, as dependencies between the building parts become more complex as the design option becomes more extensive. This means that including secondary effects is not always necessary. The impact of secondary effects on the results might be negligible if the design option under evaluation causes a small change in the building. Nonetheless, each case should consider whether or not secondary effects are to be investigated.

The system boundary needs to be specific for each individual case. Taking the case study with choice of insulation thickness as an example, if the extra insulation had been placed internally instead of externally, it would have led to a completely different system boundary. In that case, it would not be necessary to increase the intermediate floors, but the available indoor floor area would be considerably less. Decreased floor area will lead to less available area to let or sell, but, more importantly, if the functional unit is tied to the floor area it will affect the normalization of all results. Should a sandwich element construction be used as the external wall, a moderate insulation increment would have fewer consequences. This is because the inner concrete slab is load-bearing. Thus, only thicker insulation and perhaps stronger ties in the wall might be needed. An important finding from this study is that secondary effects influence the system boundary, algorithm architecture, results and the final conclusions regarding optimal building design.

Omitting secondary effects can lead to incorrect results on the optimal solutions regarding global warming potential and life cycle cost, leading to faulty conclusions regarding the design. Therefore, it is important to take them into consideration when performing optimisation studies of building design options. If secondary effects had not been thoroughly investigated, nearly half of the environmental impact of materials and one-third of the production cost could have been missed in the case study in Paper I, see Table 5. It is thus essential to take a systematic approach together with experts on different aspects of the system when identifying which processes to include. The effects and consequences evaluation (ECE) method is introduced to ease the work process in determining the correct system boundary. It provides a consistent and systematic method for involving different experts in order to consider as many secondary effects as possible when establishing the system boundary. This will complement existing research that sets criteria on the system boundaries by providing a clear workflow.

There are some problems with the selection method of relevant unit processes in the system boundary of life cycle studies because weight and environmental impact, for example, do not have a proportional relationship when there is more than one material involved. The amount of 1 kg of a particular material might have several orders of magnitude higher environmental impact in an impact category than the environmental impact of 1 kg of another material. This is something that has to be considered before an identified process is excluded from the system boundary. An issue in making calculations on buildings is that it is difficult to obtain reliable data on the material amounts used in the building, since it is not something that is recorded on a building level. Even when drawings of the building are scrutinised, there is an apparent risk of omitting materials and products that have significant impact on the calculations. HVAC installations are especially difficult to obtain data on. Unreliable data induce higher stochastic uncertainties and produce numerical results with a lower confidence level. In Paper III, this was addressed by designing a template, together with the main contractor for an office building, that made it possible to collect relevant material and product data. An LCA was conducted on the built-in materials and products, and the results are shown in Figure 9. In order to determine the products and materials having an extensive environmental impact, it is sensible to consider materials and products that have a large share of the total mass of the building. However, the study found that even though copper and aluminium were below 1% of the building mass, they contributed 25% and 33%, respectively, to the impact categories AP and EP (acidification and eutrophication potential). This means that omitting materials and products with low total mass will run the risk of overlooking significant environmental impacts of a building. This implies that negligence in collecting material data can lead to faulty conclusions about the building's total environmental impact as well as in the evaluation of design alternatives. One way to handle the issue of the cut-off criteria is to set it low enough, although further research is needed to quantify an adequate level. It is also possible to use the environmental impact to decide on the relevance of a unit process, as [73] suggests. This will indeed sort out the relevant processes, although a disadvantage of this approach is that a full life cycle impact assessment has to be carried out. The purpose of excluding the unit process to make the work more efficient is then lost.

Both the prerequisites of a building and the uncertainties affect the optimal solutions. The sensitivity analysis in Paper II indicates that the optimal solutions are unique for the chosen case study as relevant building parameters are unlikely to coincide with different building projects. For buildings with different prerequisites the optimal solutions will have a large variation, as shown in Figure 5. This means that although it is possible to make an optimisation of the insulation thickness in the building envelope and include secondary effects, the determined optimal solutions will only be valid for the investigated building project.

Including uncertainties and providing a robust estimation of the confidence level of a calculation will make the results more valuable as a decision support tool, even though it may place more effort on the receiver to interpret the results [74]. There are, as mentioned in Section 2, many types of uncertainties, but most studies only consider parametric uncertainties. This is likely because parametric uncertainties are easier to identify and manage with existing statistical methods. However, when there are large uncertainties that are not parametric, e.g., model uncertainties, there is a risk that the uncertainty analysis is misleading [51]. An example would be to compare different fans considered for ventilation. Both fans have the same specific fan power during a certain flow with low parametric uncertainty. However, one fan can be speed-regulated while the other only can be turned on or off. If the model used for the calculations only considers the specific fan power for a static flow, the model uncertainty can be much larger than the parametric. Performing a Monte Carlo simulation on this model can underestimate the uncertainty of the results. A quantified uncertainty analysis is therefore also incomplete and uncertain in itself [43]. It is thus important to be transparent about how the uncertainty analysis is carried out by stating which types of uncertainties are included and report the conclusions of the analysis in a way that does not overestimate the statistical significance of the results.

The magnitude of impact in general for different uncertainties is difficult to appraise as it is dependent on many factors, such as the goal and scope of the study, building design choices and assumptions about the future. The research question, including type of design choices to be made, will also affect which uncertainties will be important. The purpose of the life cycle study of a building will affect the uncertainties that arise. When studying insulation thickness, uncertainties related to energy use will have high importance, while for choice of flooring materials the same uncertainties might be insignificant. If life cycle studies are done to provide an assessment of a complete building, e. g., to be used in benchmarking between buildings, much work will be required to collect data about the products in the building, but the design and composition of the building will be mostly set. Therefore, most of the uncertainties in these kinds of studies are related to data uncertainty like parameter uncertainty and variability. When life cycle studies are instead used to compare different design alternatives, the data uncertainty will still be important but pertain to fewer items. Instead, uncertainties regarding choice will have a larger influence when comparing alternatives. This is because replacing some products or materials, or changing the geometry of the building, can affect the building in ways that have several possible solutions. These solutions might in turn have several possible alternatives. Another factor that influences the type and magnitude of the uncertainties is the phase the building is in when the life cycle study is carried out. Naturally there are larger uncertainties early in the design phase of the building when many choices are yet to be made, compared to when the building is more or less completed.

In Paper IV and V, it is shown that subjective choices of the study affect the (Pareto) optimal solutions set. It is possible to get diverging conclusions depending on which options are chosen. This implies that collecting more extensive and accurate data will not solve the issue of life cycle studies of similar objects with different framing arriving at different conclusions. These subjective choices are likely one reason for the criticism that one can obtain any conclusions one desires in life cycle studies. This indicates additional complexity in comparing design solutions between different buildings and making generalised statements regarding which design solutions are superior. DCP, the developed procedure in Paper IV, provides a structured way to organise and manage choices usually available in early life cycle studies of buildings.

The novelty of DCP is to manage choice uncertainty and combine it with existing methods for parameter uncertainties when using life cycle tools as decision support for building design. Using DCP makes it easier to get an overview of the possible choices and their potential interaction within the study, and furthermore enables important choices to be isolated in order to investigate them in more detail. It also helps the LCA practitioner communicate the complexity of these kinds of studies to the stakeholder. This makes it a useful complementary tool to be used together with existing tools for uncertainty assessment of life cycle studies. If DCP is implemented in studies that manage stochastic uncertainties in the LCA and LCCA of building design, like the examples mentioned in the introduction, it would likely make the studies more complex. However, it would provide a tool to not only investigate where more data is needed to improve the results and conclusions, but also which choices have the greatest impact on the study and need to be further investigated.

One of the steps in DCP includes making a decision tree or choice palette in order to provide the overview and communicate the available choices. Creating a decision tree is a common way to illustrate available choices that must be made in order to reach a decision. However, if there are many choices it can be an arduous task to draw a decision tree that is exhaustive. Paper IV introduces a choice palette that can also be constructed to obtain an overview of the choices and options (see Table 6). The choice palette provides less information as it does not describe the dependencies between options. On the other hand, it is easier to construct and provides a more condensed overview of the available choices. Including a choice palette or decision tree together with the results from stochastic uncertainty methods better illustrates what the results represent. It would provide more credibility to the performed life cycle study. Combining DCP with stochastic uncertainty methods will therefore facilitate the use of life cycle studies, which often have great uncertainties, as an early design decision tool for buildings.

As a precaution, all uncertainties could be considered for inclusion in the study during all phases of the building life cycle. However, it will probably not be feasible to analyse the effect of all possible choice combinations and to fully evaluate the uncertainty ranges of all input data used in the inventory [75]. For practical reasons, it might therefore be necessary to choose a certain range or point estimate of a parameter to get a result at all, even if the evidence for the choice is lacking. In order not to underestimate the importance of a parameter with an unknown value, it could be sensible to use a long range of possible values for that parameter. However, to provide enough information to be valuable as a decision support tool it is necessary to make choices that restrict uncertainties. To include all possible parameters and uncertainties "just in case" will likely lead to a result from which no useful conclusions can be drawn. If energy use for the building, along with its large range of possible values, is included when they are the same between all design alternatives, this could overshadow the uncertainties that are really relevant. This could mean that no significant difference is shown between the design options. If the energy use is correctly left out of the calculations, a more correct judgement can be made. This situation is different from deterministic calculations, in which the inclusion of the same energy use in both design options will affect the magnitude of the results for each option but not the difference.

Another way to limit the reported uncertainties, besides excluding unnecessary parameters, is to contemplate what kind of life cycle study will be conducted. A large number of uncertainties in the life cycle studies of building design is caused by the long timeframe that needs to be considered. In [76] future scenarios are categorised according to the purpose of the life cycle study. When using the study as a decision support tool for building design options, it would be appropriate to classify the study as predictive. A predictive study can be further classified into a forecast study or a what-if study. The forecast study, as the name implies, aims to make a correct as possible prediction of the environmental impact and costs in a likely future. The what-if study will instead make a prediction of the environmental impact and costs if a future with specified conditions unfolds. Since the future is very unpredictable for more than a few years ahead, it becomes unfeasible to distinguish between design options if all possible uncertainties should be included in the calculations, as would be the case in a forecast study. If the study is treated as a what-if study, many choices and value ranges could be limited compared to a forecast study.

Using "black box" software hides many relevant choices from the stakeholders without informing them of the impact on the results. Previous studies on life cycle optimisation of building design, mentioned in the introduction, motivate some of the author's choices. However, these studies do not provide an overview, or even mention, all relevant choices and their options. This is despite the fact that there could be several hundred or possibly several thousand combinations of options for the choices in simulations with many design options, e.g., [27]. Likewise, few consider stochastic uncertainties or changes to the system boundary. The approach suggested in this thesis provides the means to highlight uncertainties, analyse them and use this information to improve the quality of the life cycle study in a structured way. This will mitigate the problem of obtaining false certainty when conclusions are drawn while providing solid decision support. However, it might not provide decisive conclusions regarding optimal design. The approach makes it possible to identify design solutions that are suboptimal, design solutions that are promising, and a way to analyse the uncertainties in order to improve the study. More discussions on the design optimisation approach itself can be found in Paper V. Adopting the methods and procedures described in this thesis in the building industry will likely provide design conclusions with higher quality as well as save time and effort when conducting the life cycle study.

It might never be possible to provide completely decisive answers from life cycle studies – the world is too complex to be completely understood by such tools. This thesis has explored and problematised the issue of pertinent uncertainties in order to increase our understanding of the problem. Solutions that address some important concerns were presented to increase the quality of decisions based on the results from life cycle tools. It is, of course, desirable to get a conclusive answer using one optimal design option. However, the goal of obtaining this one answer should not be achieved by ignoring the stochastic uncertainty of the data and the subjective choices commonly present in life cycle studies. When describing the world accurately from a holistic perspective, which is a goal of life cycle studies, there will always be uncertainties. This is especially the case when future scenarios are considered. Most people are aware of this fact, but still present their results as point estimates that will consequently hide such uncertainties and give the illusion of a higher certainty than is really the case in the conclusions made. However, by accepting and addressing the uncertainties, one might obtain less certain conclusions, but more insight into the issues that the life cycle study targets. A result of not hiding ignorance in precision could be better-informed decisions about building design. This thesis provides, if not a complete solution, an approach to raise awareness and hence enable reducing the uncertainties in life cycle studies with the aim to lower environmental impact and building costs.

6. Conclusions

The results from this thesis show that secondary effects, choice uncertainties and material data gaps in life cycle studies of building design can greatly affect the results and conclusions. Omitting secondary effects can result in a system boundary that is not satisfactorily comprehensive. This can in turn affect optimisation studies in several ways:

- The magnitude of impact of the design option for each parameter set can be incorrect.
- The difference in impact magnitude between different design options can be incorrect.
- As a consequence, the conclusion about the optimal solutions can be incorrect.
- More extreme design options will have a higher influence on secondary effects, as dependencies between the building parts become more complex when the design option becomes more extensive.

The secondary effects are specific to each design alternative, which means that relevant technical system boundary is specific to each design alternative. Therefore, it is important to evaluate secondary effects when changes or additions are made to a design alternative. If several design alternatives are evaluated in a single life cycle study, the technical system boundary has to include relevant secondary effects for all the design alternatives. The effects and consequences evaluation (ECE) method is introduced to ease the work process of determining the correct system boundary together with the experts.

Another finding is that the result is highly dependent on many prerequisites that are unlikely to coincide with different building projects. This means that the determined optimal solutions will only be valid for the investigated building project. For buildings with different prerequisites the optimal solutions will have a large variation.

The DCP procedure that was developed provides a structured way to organise and manage choices usually available in early LCA to construct probabilistic decision support when designing buildings. The novelty of DCP is managing choice uncertainty and combining it with existing methods for parameter uncertainties when using LCA as decision support for building design. The structure of the procedure is adapted in this study to make the procedure easier to apply in building projects. Using DCP makes it easier to get an overview of the possible choices and their potential interaction within the study, and furthermore enables important choices to be isolated for deeper investigation. It also helps the LCA practitioner communicate the complexity of these kinds of studies to the stakeholder, making it a useful complementary tool to be used together with existing tools for uncertainty assessments of LCA.

Certain materials in a building can have a large environmental impact even though they make up a small share of the building's total mass. A novel finding is the significant impact (14–32%) of the technical installations in four out of five environmental impact categories in an office building. Copper and aluminium in the HVAC system significantly contribute to the impact categories AP and EP (25% and 33%, respectively). These findings highlight the importance of these kinds of products in the environmental impact mitigation of buildings. Omitting the HVAC system or materials with small amounts in a building LCA can overlook a considerable part of the environmental impact for several impact categories.

The factors investigated in this project, secondary effects, choices and material data gaps, create uncertainties that all more or less affect the conclusions and decisions regarding optimal design. Therefore, there is a need to manage them using a consistent, systematic approach. The findings from this thesis outline an approach for life cycle studies that will allow for fair comparisons between different design options for a building. The approach addresses issues such as establishing a correct technical system boundary, collecting data and managing uncertainties, especially regarding choices in life cycle studies. This will facilitate decisions among different building design solutions so that the option with the lowest total environmental impact and a reasonable cost can be chosen.

7. Future Research

This study provides an approach to specific issues related to building design decisions. However, it would be beneficial to incorporate similar issues related to LCA and LCCA in general into a more comprehensive practical guideline for building design. This future work should also address the need for more details on how to manage different kinds of uncertainties. An example would be a (ranked) list of the most common uncertainties with a great impact on the results related to different design variations. To facilitate the application of the guideline, it would be beneficial to create a digital tool that implements the advice from such a guideline, perhaps as a plug-in into existing life cycle and building information modelling (BIM) tools. The guideline could also be expanded to include other aspects, such as social considerations and dynamic uncertainties, such as energy prices and environmental fluctuations over time.

The parameter space quickly expands as more variables and possible states of these variables are introduced. When the possible variable combinations become too large, this approach will become unmanageable, as managing the input and output data, as well as the simulations, will be time consuming. There are tools available today that can calculate large parameter sets. However, there is a need to combine them with methods that analyse secondary effects in system boundaries, available choices and parameter uncertainties. Creating digital tools that do not merely take in input and provide output but could automatically set up life cycle studies considering such aspects would be of great value. Such tools would enhance the analyses of different combinations of design, choices and building parameters and provide more insightful output. They would facilitate life cycle studies that have higher quality with less effort.

Buildings are complex entities. There are usually many solutions for each design option, and conducting a case study makes the theoretical discussion less abstract. The methods and procedures for each investigated issue were therefore developed and evaluated using case studies of real buildings. A disadvantage of this approach is that the solutions might be adapted too much to the questions and issues that are apparent in the case studies, but not flexible enough to manage studies of other cases. This study has proved that the concept works, but future research should address the approach on a more theoretical level to obtain a more generalised process. This generalisation could also expand the concept to design and development of other complex products besides buildings.

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Appendix A

Table 8. Pareto-optimal design solutions for the investigated sets of options. The first column is the Pareto-optimal solutions when using point estimates. The second column is the Pareto-optimal solutions with a 70% confidence level. The third and fourth columns are Pareto-optimal solutions when the discount rate is changed. The fifth column is Pareto-optimal solutions when the reference calculation period is 100 years.

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