Environmental and Cost Assessments of Buildings

The importance of secondary effects

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List of publications

This thesis is based on the following publications, referred to by their Roman numerals:

I **The importance of including secondary effects when defining the system boundary with life cycle perspective: case study for design of an external wall**

P. Ylmén, J. Berlin, K. Mjörnell, J. Arfvidsson
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II **The Influence of Secondary Effects on Global Warming and Cost Optimization of Insulation in the Building Envelope**

P. Ylmén, K. Mjörnell, J. Berlin, J. Arfvidsson
Building and Environment [submitted]

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Publications not included in this thesis:

Experiences with LCA in the Nordic Building Industry – Challenges, Needs and Solutions

R. D. Schlanbusch, S. M. Fufa, T. Häkkinen, S. Vares, H. Birgisdottir, P. Ylmén
2016, Energy Procedia 96, 82-93

Preface

This thesis is the outcome of a collaborative research project with building sector representatives from FoU-Väst, Lund University (LTH) and SP Technical Research Institute of Sweden. The context of the work is twofold: firstly, to find practical and easy conclusions that will be directly beneficial to the building design process; and secondly, to penetrate the issues based on scientific methods and procedures. Striking such a balance is difficult and there is always a risk of promoting one side at the cost of the other. However, in this project I feel the situation was opposite and the different views gave rise to very fruitful discussions. This was due to the fact that the project members were very engaged in the research problem, and at the same time have long experiences and deep knowledge within their respective fields. I believe that this collaboration has provided higher quality results than the industry and academia could have created separately.

I would like to thank Linda Martinsson from Skanska who led the industrial side of the project. A special thank you to the rest of the Swedish industrial partners: Pär Åhman from Swedish Construction Federation, Johnny Kellner from Veidekke, Rolf Jonsson from Wästbygg and Lars Tirén from Eksta Bostads AB, who participated in valuable discussions on considerations to be made in building projects and other vital information. Financial support is also acknowledged from the Development Fund of the Swedish Construction Industry (SBUF) and the Swedish Energy Agency.

My supervisors Jesper Arfvidsson at LTH, Kristina Mjörnell at SP and Johanna Berlin at SP have supported me throughout this work. Their guidance helped me solve any difficulties, and their experience and deep knowledge inspired me to improve the quality of the work to the extent of my abilities.

Last, but not least, I would like to mention my children Lia, Julian and Tina, who bring so much joy, and the rest of my family for always being there. A special thanks to my beloved wife, Jeong Lim, whose support and love lights up my life.

Gothenburg, January 2017

Peter Ylmén

Summary in English

There is an increasing awareness that the environmental impact from the building construction phase is growing compared to the operation phase. Therefore, it is important to consider the complete life cycle of energy improvement measures, for example through life cycle assessment (LCA) and life cycle cost analysis (LCCA). Many advanced optimization methods using LCA and LCCA have been developed in recent years, for example optimization function algorithms, genetic algorithms and neural networks. In buildings a design option will in many cases affect building parts outside the induced change in the design option, in other words secondary effects. So far previous studies fully addressing secondary effects are rare, and in fact none were found. The consequences of not including secondary effects in optimization studies can be conclusions based on misleading calculation results.

The aim of the current project was to develop and evaluate a procedure that makes it possible to compare different options for building design with regard to environmental impact and cost.

To get reliable results it is crucial to set up correct system boundaries for the investigation, but it is often difficult to understand complex product systems because of the cascade effects of consequences that can be induced by even small changes. In this work the effects and consequences evaluation (ECE) method is introduced to systematically identify and organize the effects and consequences of a design change in parts of a complex system. The method is applied in a case study of building envelope insulation for a new building to investigate the importance of correct system boundaries, as well as examine in detail how secondary effects will affect optimization studies. This is done by using LCA and LCCA in a parameter study of the insulation thickness in the building envelope of a concept apartment house. Altogether 64 combinations of insulation thickness for the external wall, slab and roof are evaluated using LCA and LCCA with and without secondary effects.

Findings from this study show that secondary effects influence the system boundary, algorithm architecture, results and the final conclusions of optimal building design. Therefore, it is important to take them into consideration when performing optimization studies of building design options. The findings from this project outline a procedure that will allow for just comparisons between different design options for buildings. This will help facilitate the choice between different building design solutions in order to choose the option with the lowest total environmental impact and a reasonable cost.

Sammanfattning på svenska

Det finns en stigande medvetenhet att miljöpåverkan från produktionsfasen av byggander ökar jämfört med driftsfasen. Det är därför viktigt att ta hänsyn till hela livscykeln vid energiförbättringsåtgärder, till exempel genom livscykelanalys (LCA) och beräkningar av livscykelkostnad (LCC). Under de senaste åren har många avancerade optimeringsmetoder som använder LCA och LCC utvecklats, till exempel optimeringsfunktioner, genetiska algoritmer och neurala nätverk. I byggnader kommer designalternativ i många fall att påverka byggnadsdelar utanför den avsedda förändringen i designalternativet, med andra ord sekundära effekter. Studier som i tillräcklig omfattning tar hänsyn till sekundära effekter är ovanligt, i själva verket har inget ingen funnits. Konsekvensen av att inte inkludera sekundära effekter i optimeringsstudier kan vara slutsatser som är baserade på missvisande beräkningsresultat.

Målet med det här projektet var att utveckla och utvärdera en procedur som möjliggör jämförelser mellan olika designalternativ för byggnader avseende miljöpåverkan och kostnader.

För att få tillförlitliga resultat i en undersökning är det avgörande att fastställa korrekt systemgräns, men det är ofta svårt att överblicka komplexa produktsystem på grund av de kaskadeffekter som kan uppstå även vid små förändringar. I det här arbetet är metoden effekt och konsekvensutvärdering introducerad för att systematiskt identifiera och organisera effekter och konsekvenser vid förändringar av delar i ett komplext system. Metoden tillämpas i en fallstudie av isoleringstjocklek i klimatskalet vid nyproduktion av en byggnad för att undersöka vikten av korrekta systemgränser. Samtidigt undersöks i detalj hur sekundära effekter kan påverka optimeringsstudier. Vid utförandet används LCA och LCC i en parameterstudie av isoleringstjocklek i klimatskalet för ett flerbostadshus. Sammanlagt 64 kombinationer av isolertjocklek i yttertak, yttervägg och bottenplatta utvärderas med hjälp av LCA och LCC med och utan sekundära effekter.

Iakttagelser från den här studien visar att sekundära effekter påverkar systemgränsen, algoritmarkitektur, resultat och slutsatserna om optimal design. Det är därför viktigt att ta hänsyn till dem vid utföranade av optimeringsstudier för byggnaders utformning. Resultaten från det här projektet utpekar en procedur för precisa jämförelser mellan olika designalternativ för byggnader. Det kommer att underlätta vid val av olika designval så att alternativet med lägst total miljöpåverkan till en rimlig kostnad kan väljas.

List of abbreviations

ECE	Effect and consequences evaluation
EPD	Environmental product declaration
GWP	Global warming potential
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
PCR	Product category rule
PV	Present value

Environmental and Cost Assessments of Buildings: The importance of secondary effects

1 Introduction

1.1 Background

For many years the Swedish building sector has focused on making buildings more sustainable, wherein operation energy use has been considered especially important from an environmental perspective. To reduce the building energy demand, extra insulation and installations, like ventilation heat recovery, have been installed in the buildings, which lead to increased emissions 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, for example Larsson et al. (2016) show that the emissions from the production phase and operation phase are comparable in magnitude. This means that to find solutions with the lowest total emissions at a reasonable cost, the whole life cycle of buildings must be considered.

Currently, building designers commonly use simplified environmental analyses that consider a selection of environmental aspects such as waste and toxic compounds in the materials. More refined methods that in an objective way compare different design options are needed to optimize buildings with regard to environmental impact and cost for the complete life cycle. Appropriate tools to consider these aspects are life cycle assessment (LCA) and life cycle cost analysis (LCCA).

The idea of LCA is to summarize all the emissions from a product, from raw material acquisition to final disposal, and calculate the potential environmental effect from 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 eighties, Gustafsson and Karlsson (1989) developed a mathematical model, optimal energy retrofit advisory (OPERA), that deals with energy retrofits and how the strategy can be optimized for the life cycle cost (LCC) of a building. In Jonsson et al. (1998) seven concrete and steel building frames were evaluated using LCA. These are some of the first examples of LCCA and LCA applied for buildings in Sweden with the aim of finding the design with the least environmental impact and lowest cost.

At the beginning of the millennium, the Swedish building sector started to utilize 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 (EPD) based on LCA are being developed.

1.2 Life cycle assessment

The concept of LCA started around the seventies and was mainly used to evaluate different options for packaging. In 1997, LCA became a standardized procedure described in standards ISO 14040-43, which were later replaced by ISO 14040:2006 and ISO 14044:2006 (Swedish Standards Institute, 2006a,b). The standards provide a framework for conducting LCA but do not provide details for every given situation. Reality is complex and there are often many different choices and assumptions to be made by the LCA practitioner 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:

- goal and scope definition
- life cycle inventory (LCI)
- life cycle impact assessment (LCIA)
- interpretation

The goal and scope definition is crucial to outline LCA. It defines the goal of the study, assumptions, limitations and other boundaries that will affect the result and interpretation of LCI and LCIA. One of the most important decisions made in the goal and scope is the definition of the functional unit to which all of the collected data will be normalized. Another is the choice of allocation methods. Studies of the same product with different goal and scope might produce different results on the environmental impact, meaning that results might be incomparable between studies if the goal and scope are different.

In LCI, all resources used and emissions from the products's life cycle are identified and calculated. This is usually the most time consuming part of LCA. The summarized resources and emissions are then weighted for relevant environmental parameters and analyzed in LCIA. Conducting LCA is an iterative process, as commonly new findings during interpretation of LCI or LCIA can lead to reformulation of the goal and scope or expansion of the LCI.

When doing LCA of a product there are two main types — attributional (bookkeeping, accounting) and consequential (change-oriented) (Baumann and Tillman, 2012). The attributional method states the environmental impact for the product as it is. This method is useful for environmental assessment or comparison between different products with the same function. The consequential method is more suitable to investigate how changes to a products manufacturing process affect the environmental impact of the system. This is preferable when doing optimizations for moderate changes in building design. Another advantage of the consequential method is that an evaluation of the complete system is not necessary, only the differences induced by the change. However, the attributional methodology is also needed to get information on the built-in products used in the calculations. The theory and implementation of attributional and consequential LCA are both well established within the research community (Baumann and Tillman, 2012). However, LCA is a generic method and there is not a consensus on how to carry out all of the procedures of the methods in detail.

In a consequential assessment it can be practical to divide the investigated system into a foreground system, that includes processes where changes through active choices can be applied, and a background system with the processes that are implicitly affected by the foreground processes (Baumann and Tillman, 2012). Dividing the system into these two groups will create a better understanding and facilitate the investigative work.

Buildings consist of thousands of products and have complicated construction processes with many stakeholders involved. Since buildings with few exceptions are also unique with regard to design, use and location, it is in praxis nearly impossible to make a similar detailed LCA for a single product such as a soap bar, nail or screw. Simplifications and the use of average data are needed to make the workload acceptable. There are databases that provide sorted environmental and material data for products. However, these are often not adapted for complete buildings without considerable management of the data. A new type of databases are setup consisting of LCA-based EPDs for building products.

An EPD is an environmental declaration based on attributional LCA to be used when comparing products, although the declaration itself only gives the necessary information to make such a comparison. It presents the environmental load for midpoint impacts, for example global warming and acidification potential, and it does not give any rating if the product has good or bad environmental performance. Such a comparison must be made outside of the EPD system. The procedure to produce an EPD is described in product category rules (PCR), which state how to define the goal and scope, for example, the functional unit, system boundaries, allocation procedures, data quality, and recycling principles. Hence, EPDs based on the same PCR are comparable. Each organization that provides EPDs develop and manage their own PCRs. Thus, EPDs on the same product category cannot be compared if they originate from different organizations.

1.3 Life cycle cost analysis

A method to make LCCA is described in standard ISO 15686 (Swedish Standards Institute, 2008). 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 of LCCA is that costs occurring in the future are discounted, compared to the costs occurring today. The reason is that money available can now be invested or deposited somewhere else, for example in a bank. If the cost occurs in the future you will gain the interest compared to if it was deposited at the present time. Thus, a cost incurring in the future will have a lower value than the same cost today. This is called discounting the costs and the rate used for the calculations is called the discount rate. The rate can either be real or nominal, but it is recommended in the standard to use the real discount rate as it will make future costs easier to predict.

The discount rate is decided based on the available investment options for the investor, financial risk with the project, and the expected return. This means that it is very specific to each project, depending on the investor and the conditions of the project. If an investor has two different potential building sites, for instance in the city center and the outskirts, a different higher rate should usually be applied since it is a higher risk for low occupancy and yielding lower income on the outskirts of the city. When calculating the real present value the formula

$$\text{PV} = k \cdot C = \frac{C}{(1 + r_d)^n}$$

is used, with C as cost, r_d the discount rate and n the number of years until the cost occurs. k is called the discount factor, and examples of how the discount factor is influenced by different rates are shown in Figure 1. For high rates future costs and incomes will be less important than for low rates.

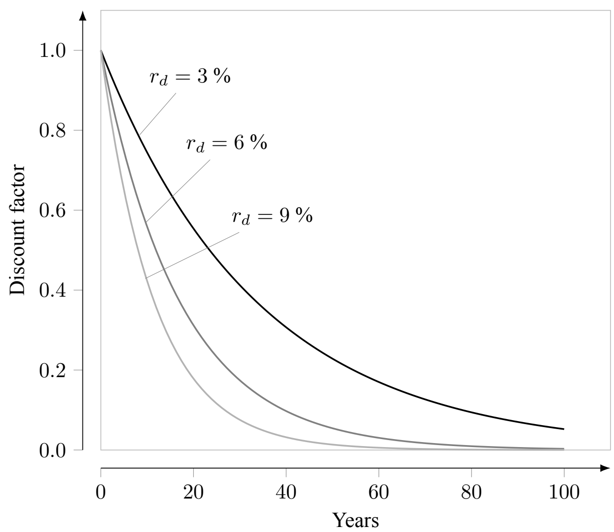

Figure 1: The plot shows how the discount factor (k) is decreased over time for different rates.

Buildings have nearly always longer lifetimes than the calculation period. It is then appropriate to specify a residual value of the building products and equipment since they will keep fulfilling their purpose in the building after the calculation period is finished. This means that although they will not be sold they still have a residual value. This approach gives more robust calculations. If, for example, a system has the technical lifetime of 10 years and thus specifies that reinvestment should be done every tenth year, it will affect the result whether the calculation period is set to nine or eleven years. If, on the other hand, the residual value is considered, the effect of the reinvestment will be smaller. This would be more correct as the residual value will be considered and that would lessen the cost for the nine years of the system that is not included in the calculation period.

1.4 Former work on LCA and LCCA for optimization of building design

Cabeza et al. (2014) made an overview of the literature in LCA, life cycle energy analysis and LCCA for the building sector, wherein they stress that although LCA is a mature method for simple products and materials there are new challenges when it comes to buildings. This is due to:

1. Buildings are site specific and local environmental impacts might need to be considered.
2. Buildings consist of many products with their own life cycles, making the data gathering and simulation difficult.
3. Buildings have long lives, due to the long operation phase. This leads to major uncertainties in the modeled scenarios.
4. Design choices might effect the indoor environment, behavior and performance during the operation phase. Typical LCA methodologies do not address these impacts even though they might contribute most to the total impact.
5. It is encouraged to use recycled materials in buildings and such data are usually not included in LCA databases.

Cabeza et al. (2014) also state that it is difficult to compare different case studies since the conditions like climate, location, and building type, for example, are not the same. The high variation for the investigated studies are the scope (only materials or whole building), which in turn affects the system boundaries. Other important parameters that differ are life time considerations, functional unit, building typology, and location.

LCA and LCCA have been combined in several optimization studies. Verbeeck and Hens (2007) described a global methodology to optimize concepts for extremely low energy dwellings, taking into account energy use, environmental impact, and financial costs over the life cycle of the buildings. It was divided into three parts: optimization, LCI and LCCA. The focus was energy efficiency measures in residential buildings by comparing different design options with a Belgian reference building. To make the optimization, a genetic algorithm was used with Pareto optimization. A genetic algorithm approach was chosen due to the complex nature of buildings and the large amount of parameters involved. Although methods using the genetic algorithm enable a fully automated process by setting up extra constrains, this would lead to greatly increased complexity of the calculation functions. Hence, 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 insulation homogeneity of the building envelope. A solution with 2 cm roof insulation and 20 cm façade insulation was found, but is not realistic to actually carry out. Using Pareto optimal solutions is preferable when dealing with optimization problems that have multiple objectives, and the method deducts several different optimized solutions that can be further considered in a decision process where different target groups have various project goals (Verbeeck and Hens, 2007).

To minimize lLCC and CO_2 equivalent emissions from buildings, Fesanghary et al. (2012) used a harmony search algorithm. They stated that optimization methods usually have difficulty handling discrete numbers, which might lead to optimum values that are not feasible to use in a real building. To handle this only values available on the market were used in the optimization. Ostermeyer et al. (2013) described an approach to conduct life cycle sustainability assessment for refurbishing buildings. In this method the possible solutions were not calculated from continuous values as they argued that the measures to be evaluated should be identified by experts to remove unrealistic options from the beginning, although they concluded that this might lead to the fact that some good solutions may not be considered. In Azari et al. (2016) 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 utilized to optimize the external wall and windows for an office building with regard to environmental impact.

In buildings, a change in design will in many cases affect building parts outside the induced change. 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 have to be elongated to support the increased wall thickness. The wider floors 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. The above mentioned studies provide new procedures on environmental and cost optimization of buildings but do not fully address secondary effects. The consequences can be conclusions based on misleading calculation results when the methods are applied without including secondary effects.

Buildings are complex systems with many functions, products and stakeholders; therefore, a holistic approach is necessary when evaluating the building design. In Sweden, 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 will 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.

In our research project it was investigated how to compare different design options in the building design phase with regard to the environmental impact and cost. The problems with LCA for buildings, described by Cabeza et al. (2014) 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. Focus in the current work has been on the identification of secondary effects, and how to consider these in optimization 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 an apartment building.

1.5 Aim and objectives

The aim of the work was to develop and evaluate a procedure that makes it possible to compare different options for building design with regard to environmental impact and cost.

1.6 Scope and limitations

The focused design options were different insulation thicknesses of the building envelope, although the procedure can be adapted to other design options.

To limit the study, global warming potential was considered as an environmental impact. The procedure will, however, be similar for other environmental impact categories commonly used in LCA such as acidification and eutrophication potential.

Only materials that are built into the construction were considered. Material spillage from production and interior surface materials such as wallpaper and flooring were outside the scope of the study. Both issues can be important considerations in the life cycle of a building but would have had a negligible impact in this particular investigation since they would occur in all options. Site activities not directly related to the building, such as transport of workers from their homes to the site, consumable supplies and site establishment, were also outside the scope of this study.

2 Methods

The work was a close collaboration between academia and industry stakeholders. It started with an iterative process in which different approaches for implementations were discussed at meetings with all involved stakeholders. Between meetings the conclusions from the gatherings were used to investigate state of the art through literature studies and contact with external stakeholders in the building sector. This resulted in new approaches or modifications of existing ones. After several discussions the work group converged with research questions that were relevant for the Swedish building sector and had not yet been addressed in papers. One conclusion was to conduct a case study of an apartment building. The building process and design for apartment buildings are more similar between projects than, for example, commercial buildings, which widens the scope of the results. Nonetheless, buildings are complex entities and there are commonly many solutions to each design option. Conducting a case study limits the degree of freedom, gives tangible results, and makes the theoretical discussion less abstract.

2.1 Case study of envelope insulation for an apartment building

To get realistic input and output data a case study was carried out on a real concept apartment house developed by Skanska AB, with some construction details altered in order to make it more representative of typical building practice in Sweden. Since it was a concept house 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 (Figure 2). There was no building area restriction and thus the added insulation could be placed externally to keep the available living space the same for all design options. The local regulations in Gothenburg allow for a larger building area if the property has enough available space and the purpose is increased heat insulation. For city areas with less available space this assumption might not be valid.

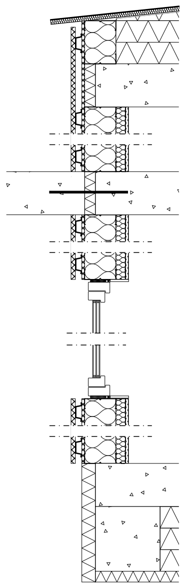

Figure 2: A section sketch of the reference building.

2.2 Effect and consequences evaluation

To determine possible system boundaries the ECE (effect and consequences evaluation) method was developed. In this method the possible effects of a design option are identified. For each effect, the possible consequences are then determined. The procedure is repeated until all correlated consequences and effects are found. Each unit process in the obtained system can then be kept or removed based on a cut-off criteria. Instances might occur where several competing consequences are identified. That means there is a choice to be made and the unit process is then placed in the foreground system. Ideally, all diversities would be modeled as different scenarios, but for practical reasons, for example lack of resources, it may not always be feasible to assess all possible choices. Some options might then be left out if doing so is consistent with the goal and scope of the study. Typical effects that can be applicable for a building include changes in volume, surface area, weight, energy, power, cost, construction time, moisture risks, fire safety, indoor environment, acoustics, accessibility for disabled people, security, and stormwater management. These can be further divided or grouped together. For example, energy could be split into heat transmission, heat storage and solar gain.

The general procedure for the ECE method consists of the following steps:

1. Clearly describe the design option to apply.
2. Decide on a suitable functional unit for the affected system under evaluation, not only for the life cycle of the design option.
3. Identify which effects the design option is likely to induce by itself.
4. Determine the consequences each effect might have on the system. With consequences we mean adjustments that have to be made both inside and outside of the actual design options life cycle.
5. Similar to point 3, identify effects that the found consequences are likely to induce by themselves.
6. Similar to point 4, evaluate the additionally consequences each effect of the consequences might have on the system.
7. Repeat step 5 and 6 until no more effects and consequences can be found.
8. The possible system boundary is then obtained by describing the design option and all of 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 to include the process by comparing to the goal and scope of the study.
10. Group the processes into foreground and background systems.

An example of a resulting system using the ECE method is illustrated in Figure 3. The changes are compared to the initial design and a change in material means that the replaced material is saved, since it will not be used in the system if the change is implemented. Therefore, the replaced material will have a negative value in the calculations.

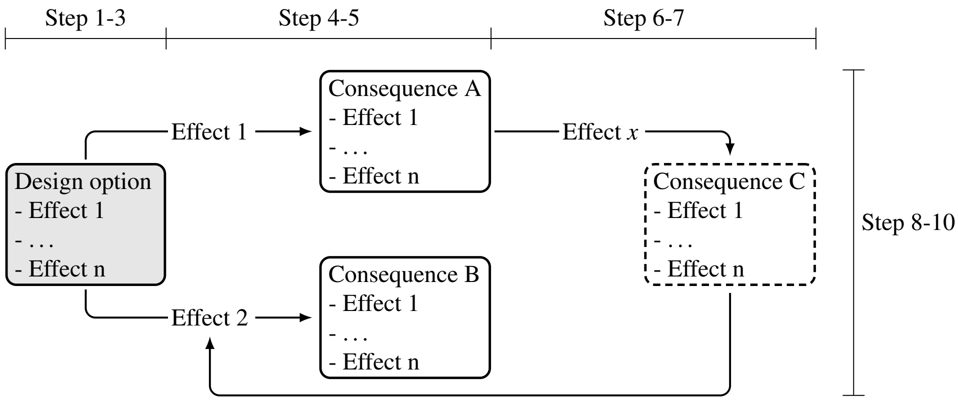

Figure 3: An example of the ECE method. The design option is defined and its possible effects are identified. Effect 1 and 2 lead to the consequences A and B respectively, which in turn will have their own effects. Effect *x* in Consequence A will induce Consequence C. In C there are no choices to be 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 inflict any consequences.

2.3 Goal and scope

The technical system boundary was established using the ECE method considering the effect on volume, surface area, weight, energy, power and LCC since these effects are most likely to incur significant consequences in this particular case. With the ECE method the dependencies between different building elements were considered. In this case study, increased wall insulation will lead to increased external wall area (façade), adjustments on the floor and ground slabs to support the thicker wall, as well as adjustment of the roof to maintain the overhang of the eaves. The magnitude of the environmental and economic impact of adjusting the roof and ground slab are dependent on the amount of roof and ground insulation used, as the increased volume will be even larger for thicker insulation when the roof and slabs are elongated. This dependency works both ways. In other words, the impacts of adding roof and ground insulation are dependent on the wall thickness, as the area of the insulation layers will be larger for thicker walls. The system boundary is illustrated in Figure 4.

To find the insulation thicknesses of the building envelope that induce the lowest environmental impact and life cycle cost, a parameter study was carried out using results from LCA and LCCA. The functional unit was set to 1 m^2 A_{temp}, which complies with Swedish laws and regulations for 50 years. The definition of A_{temp} is the total floor area intended to be heated above 10 °C inside the building envelope for all floors, including shafts, staircases, internal walls and similar entities, with the exclusion of garage areas (National Board of Housing, Building and Planning, 2015).

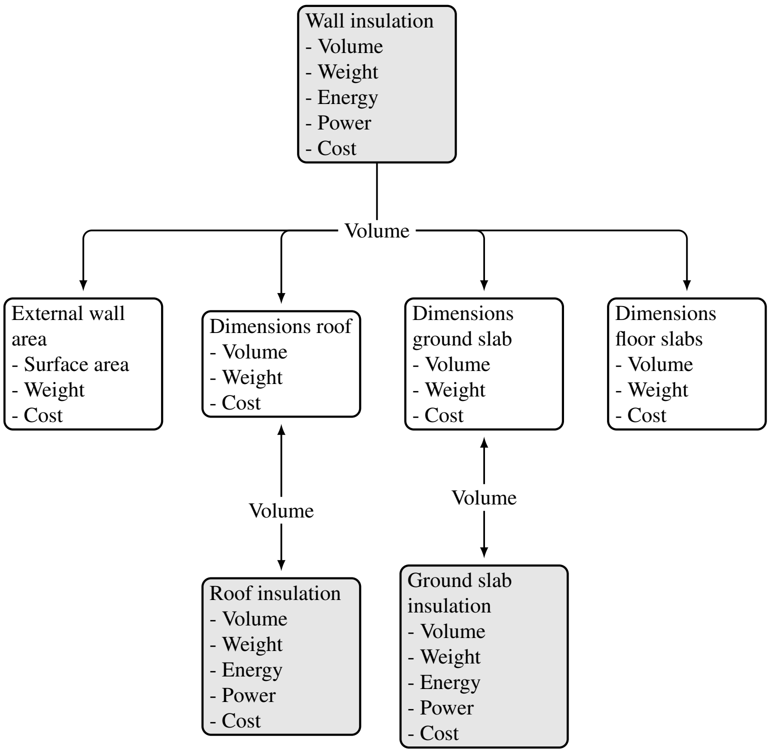

Figure 4: The system boundary for the investigated design options (gray boxes), including ground, wall and roof insulation and their secondary effects (white boxes).

2.4 Calculations

All variations were compared to the baseline case that consists of 190 mm wall insulation and 200 mm insulation in the roof and beneath the ground slab, see Table 1. This baseline design was used as a benchmark for the other calculations, and therefore its global warming potential and costs are put to zero and only the deviations from this baseline design are considered in the calculations. The different insulation thicknesses were chosen from common dimensions used in Sweden and resulted in 64 insulation combinations altogether.

The building life cycle was divided according to EN 15804 (Swedish Standards Institute, 2012), and the data were foremost gathered from environmental product declarations that contain specific data for chosen products. This facilitated data gathering and calculations since EPDs contain relevant product information in an aggregated form. If no declaration was found, a declaration for a similar product was used instead.

Table 1: Insulation thicknesses for respective element in the building envelope that are used in the calculations. Top row shows the baseline to which all the values were benchmarked against.

Wall insulation	Roof insulation	Ground slab insulation	
45 + 145 mm	200 mm	200 mm	*Baseline*
45 + 120 + 145 mm	300 mm	300 mm	
45 + 120 + 220 mm	400 mm	400 mm	
45 + 220 + 220 mm	500 mm	500 mm	

If a replacement product declaration was also lacking, the environmental impact was calculated using Simapro v8.0 (PRé Consultants B.V., 2016) with data from Ecoinvent 3 (ecoinvent Centre, 2016). The amount of material was estimated from drawings in combination with data found in Sektionsdata v4.18 (Wikells Byggberäkningar AB, 2016), which is a database that contains costs, man-hours and material use for Swedish building materials and constructions. Production and replacement costs, as well as man-hours, were therefore also obtained from Sektionsdata.

Energy and power use were calculated in the simulating software EnergyPlus 8.2.7 (U.S. Department of Energy Building Technologies Office, 2016) with the help of Therm 7.3 (Lawrence Berkeley National Laboratory, 2016) and Heat 3 (Blocon, 2016) to calculate thermal bridges. The calculation of the energy use in the building has been simplified by making a dynamical energy calculation for one year and assume that this will be the average yearly energy use for the following 50 years. LCC was calculated according to European Union regulations and guidelines (European Commission, 2012a,b). The assumed discount rate for the costs calculations was set to 5 % and energy cost 1.0 SEK/kWh.

If the calculation period is not a multiple of all the products' technical lifetime, situations may arise where unlikely reinvestments are made that will give unrealistic results. If, for example, a product has the technical lifetime of 40 years and the calculation period is set to 50 years, the product must be replaced within the 50-year period. If the building will be demolished after 50 years, it is unlikely that the product will be replaced with a similar one that also has a technical lifetime of 40 years, especially if big resources are needed for the replacement. If the building will be operational after 50 years, it will make an unfair comparison that all of the resources of this new product are allocated within the calculation period. If the calculations are made without these considerations the results will be very sensitive to choice of calculation period. To minimize the effect of expected lifetime of the building compared to products and in order to get more robust calculations, we assume that the building will still be used after the 50 years in the functional unit and that the total environmental impact will be allocated proportionally to the time it is used in this life cycle and the lifetime remaining after 50 years. In the example described above it means that only one fourth of the resources will be used for the replacement. The reason being that if the building is demolished after 50 years, a less resource intensive replacement will be used, or if the building is operational after 50 years the remaining resources will be allocated to the time after the first 50 years.

In this study there are two objectives (low cost and low environmental impact) that are to be optimized simultaneously, therefore, the Pareto optimal solutions were calculated with regard to the global warming potential and LCC.

The optimal insulation thicknesses in the building envelope will be dependent on the prerequisites set up in the study, and many of these prerequisites are uncertain in building projects. For this reason a sensitivity analysis was conducted to examine the robustness of the results.

3 Main results

Only the most essential results are presented in this chapter. More detailed data and results with regard to system boundaries, energy simulations, LCA, and LCCA are available in Paper I and II in the appendix.

In Figure 5, the Pareto optimal solutions from the parameter studies with and without secondary effects are plotted in the same chart to emphasize the difference. If only increased insulation in the roof construction is added the secondary effects will be negligible and the results are therefore similar in both cases. In the case that secondary effects are not included, the Pareto optimal design options with thicker wall insulation will have less environmental impact at a lower LCC. This will promote decisions to use thicker insulation in the building envelope. The difference in magnitude of global warming potential and LCC between the design options is also affected, as well as the relationship between the two impact categories. This means that if secondary effects are neglected it can lead to wrong conclusions on optimal building design with regard to global warming potential and costs.

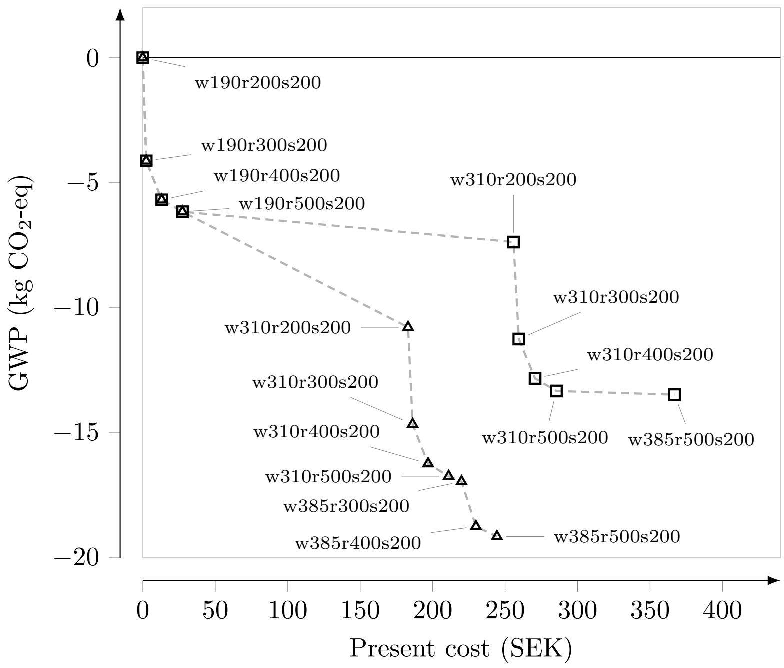

Figure 5: Pareto fronts when secondary effects are included (squares) and when they are excluded (triangles) in the same plot. The id refers to insulation thickness in mm for walls (w), roof (r) and ground slab (s).

The change of prerequisites that incurred the largest difference in environmental impact and cost compared to the original simulation were ventilation heat recovery, different energy emissions, rise in future energy prices, and lower discount rate. The Pareto optimal solutions for these options are plotted in Figure 6 together with the original calculation with and without secondary effects. Omitting secondary effects will underestimate the LCC, leading to the lowest cost of nearly all insulation combinations for each investigated variation. Only insulating the roof and using a discount rate of 3 % will give a slightly LCC. At the same time, the reduction in global warming potential will be overestimated without secondary effects, and only higher energy emissions will have a lower global warming potential for the same insulation combinations. The calculations without secondary effects also provide 11 possible Pareto optimal solutions, which is more than any other studied variation. In contrast, the variation with lower energy emissions only has two Pareto optimal solutions.

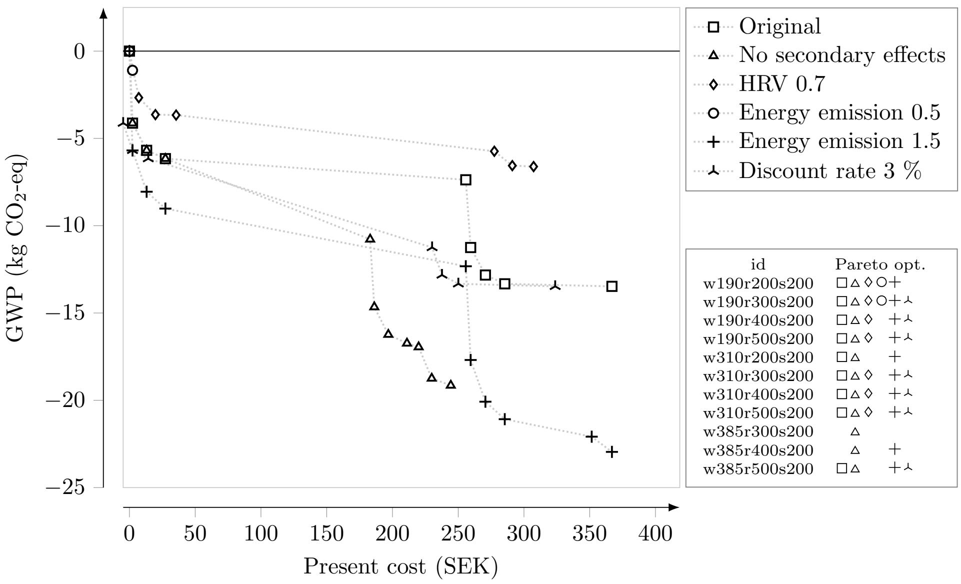

Figure 6: Pareto solutions for the variations in the sensitivity analysis. The solutions in the cluster to the upper left all have wall insulation thickness 190 mm. In general, solutions with more insulation are placed further down to the right for each variation of calculation parameter. The box below the legend shows the id of the Pareto optimal solution for each variation. The id refers to insulation thickness in mm for walls (w), roof (r) and ground slab (s).

4 Discussion

The aim of the work was to develop and evaluate a procedure that makes it possible to compare different options for building design with regard to environmental impact and cost.

The iterative approach used and collaborations between academia and industry stakeholders required patience, as there were more viewpoints to address than in a solely academic research project. Several early suggestions were rejected or required large revisions. However, we do believe that it provided higher quality results since the objections raised during meetings meant that more aspects of the problem were considered.

An important result from the procedure was to identify the problem with secondary effects and fulfill a just comparison through the ECE method. The method identifies and select relevant processes and provides a solution on how to structure the work process and present the results in a pedagogical way. In this study the ECE method was applied to define the relevant system boundary in a change-oriented approach. However, the method is equally applicable in attributional LCA. An exception being that the last step to divide the unit processes in foreground and background systems is not pertinent to attributional LCA.

The methodology used in the parameter study is straightforward by varying three variables in predefined sets and calculating the results. In multi objective optimization the Pareto optimal solutions can be evaluated. An advantage to labeling the results is the increased transparency in examining how changes in the variables affect the system. However, 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.

The results from this study show that omitting secondary effects can result in a system boundary that is not satisfactorily comprehensive. This can in turn affect optimization 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 of optimal solutions can be incorrect; and
- more extreme design options will have a higher influence on secondary effects, as dependencies between the building parts get more complex when the design option gets more extensive.

The sensitivity analysis indicates that the optimal solutions are unique for the chosen case study. For buildings with different prerequisites the optimal solutions will have a large variation. Another finding is that the secondary effects impact the results to an extent that is comparable to a large variation of the simulation prerequisites.

In this work, only one environmental impact and LCC were considered. This simplifies the presentation of results, as visual interpretation of a Pareto front in more than two dimensions is difficult, and allows the reader to easily follow the theoretical arguments made. However, the number of dimensions does not restrict finding Pareto optimal solutions. The influence of secondary effects is also likely to be significant for other environmental impacts than the global warming potential. The conclusion that secondary effects should be examined and managed within design optimizations will therefore also be valid for LCA that considers several environmental impacts.

The functional unit will have an impact on the evaluation of system boundaries. Conducting LCA on wall insulation makes several suitable functional units available, for example: heat resistance in a 1 m^2 wall per X m^2 of living area, or an apartment with 2.5 persons used for 50 years. If the functional unit is decided as a single building, internal insulation will have different implications than if the functional unit was a 1 m^2 heated floor area. It is also critical to consider the functional unit as the values have to be normalized towards it. Therefore, it is also important to make certain that the function of the building is not changed due to consequences induced by the design option. If a change in function is inevitable, the functional unit should be revised. It is common to relate the functional unit to floor area. A slight problem is that floor area is an ambiguous term. In Sweden, several definitions of floor area exist that will give different total areas in a building, although the Swedish regulations use heated floor area A_{temp}. For international studies the problem is even larger as more definitions are available.

The system boundary will be very specific for each individual case. If the extra insulation had been placed internally instead of externally, it would lead 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 out or sell, but, more importantly, if the functional unit is tied to the floor area it will affect the normalization of all results. Should sandwich element construction be used as the external wall, a moderate insulation increment would have fewer consequences. The reason is that the inner concrete slab is load bearing. Thus, only thicker insulation and perhaps stronger ties in the wall might be needed. A comparison between the three construction alternatives will therefore give an even larger and more complex system boundary. A solution might be to first look at the optimum wall for each separate construction and then conduct a new study looking only at the three optimized results.

Another problem for buildings compared to many other products is the long timeframes. In Sweden, residential buildings are expected to last for at least 50 years. Obviously, over such a long period many changes will occur that affect the environmental and economic conditions. Examples include emissions and costs of energy production, maintenance, replacements and waste handling. These events will increase the uncertainty of assessments results. A related issue is when major replacements, refurbishments or changes of activities occur in the building. When windows are replaced it will likely be with new windows that have better performance, for example, lower U-value or higher solar transparency. This can affect the building to such a degree that it should be considered a different product. Similar implications arise if the activities and building use are changed such as changing the ground floor from apartments into office space.

The fact that emissions from building operation energy can widely vary depending on future energy scenarios will have an implication on whether or not to implement energy improvement measures. A reason for this is that the production of materials and construction is carried out in present time, while production of building operation energy is made in the future. The emissions from production of many building materials are heavily dependent on the energy used in the process. This means that energy with large environmental impact is used in the present production to lessen the use of cleaner energy in the future. As shown in Figure 6 not many insulation combinations will lower the total global warming potential compared to the reference case if the average energy emission for the next 50 years is reduced to half. However, this does not account for the possibility that if energy efficient solutions are not produced today, the emissions from future energy production will be larger due to higher demand. A solution would be to improve the production process and lower the environmental impact of the building materials in the near future.

The Pareto optimal solutions from the simulations with heat recovery ventilation are different from those without heat recovery. This indicates that the common approach to first optimize the building envelope and then choose suitable installations can be misguided, as it leads to higher total emissions and costs than if the installations and building envelope are optimized together. In buildings with high performance installations that reduce the space heating demand, such as heat recovery, it could be beneficial with thinner insulation. The result also indicates that a top down perspective of the system is important when evaluating building design options.

5 Conclusions

To make correct evaluations of design options of buildings using LCA and LCCA, it is important to carefully set up a correct goal and scope of the study. Omitting secondary effects can lead to finding incorrect optimal solutions with regard to global warming potential and LCC, which in turn may lead to wrong decisions on building design. Therefore, it is important to take secondary effects into consideration when performing optimization studies of building design options. The ECE method was introduced in this project to ease the work process in finding the correct system boundary together with the system experts in a systematic and consistent approach.

The result can be highly dependent on many prerequisites that are unlikely to coincide with different building projects. This means that although it is possible to make an optimization of the insulation thickness in the building envelope and include secondary effects, the optimal solutions found will only be valid for that specific investigated building.

Using more envelope insulation may lead to a higher total environmental impact when the whole life cycle is considered, even though the operation energy is lessened. If the trend with energy improvement of buildings and using cleaner energy continues, it is important to lower the environmental impact of the production of building materials and products. Otherwise, the energy improvement measures might become counterproductive. To avoid sub optimizations it is important to have a top down perspective and look at the complete system related to the design option.

The findings from this project outline a procedure that will allow for just comparisons between different design options for a building. This will facilitate the choice between different building design solutions so that the option with the lowest total environmental impact and a reasonable cost can be chosen.

6 Future research

The results from the presented work deals mainly with design of the goal and scope of the study. However, there are other aspects that will have a great impact on the results in LCA and LCCA. Assumptions and uncertainties in the input data can give large deviations in the output of the calculations. A related issue is the long timespan for building use, which gives rise to many possible future scenarios. In future work it would be interesting to examine the possibility to combine dynamic LCA with probabilistic methods. Dynamic LCA will make it possible to adapt input parameters over time and probabilistic methods facilitate expressing input and output as distributions instead of discrete values, which allows for more precise results.

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Scientific publications

Author contributions

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Paper I: The importance of including secondary effects when defining the system boundary with life cycle perspective: case study for design of an external wall

I did the research and wrote the paper. JA, KM and JB gave feedback on the content and reviewed the article before it was submitted.

Paper II: The Influence of Secondary Effects on Global Warming and Cost Optimization of Insulation in the Building Envelope

I did the research and wrote the paper. JA, KM and JB gave feedback on the content and reviewed the article before it was submitted.