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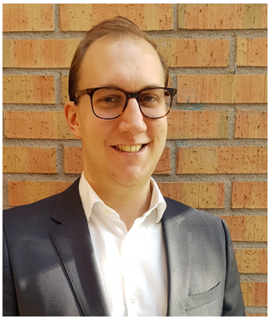

Rikard Sundling is a researcher in construction management, with a focus on the renovation of buildings. During his PhD studies, he was involved in both national and international research projects concerning the renovation of multi-family buildings. His earlier studies included a Master's degree in Civil Engineering. Rikard lectures in construction management, facilities management and project management.

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Rikard Sundling

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Abstract

In Sweden, housing accounts for about 23% of all energy consumption. Sweden wants to reach net zero carbon emissions by 2045; as such, it is likely that energy-saving measures for housing will be needed. Many existing buildings have been in operation for 50 years or more and are therefore in need of modernisation. At the same time, the population is increasing and so is the rate of urbanisation, which is why there is, and will be for the foreseeable future, a need for more housing. Energy-efficient renovation and vertical extension of buildings are potential solutions to these three needs.

In this dissertation, three case studies are presented. In the first, buildings which were renovated to incorporate both energy saving measures and vertical extensions were assessed from both a financial viability and an environmental performance perspective. In the second, four different cases of vertical extensions were investigated, two which had been realised and two of which were still in the planning stage, in order to study the development process for extending buildings vertically. The third case study deals with the financial viability of energy-efficient renovation concepts with a focus on prefabricated multi-active facades.

Overall, the studies reveal financially viable renovation concepts which can contribute to environmental performance. However, the analyses are sensitive and even small changes can alter the results; in addition, the actual outcome may differ from the results of the analysis, since the renovated buildings are planned to last for decades. While describing the development processes and the success factors can ease project realisation, renovations are complex projects and their effects are not completely beneficial.

This research contributes to both practitioners and researcher by highlighting and discussing several factors which can influencing the outcome of renovation projects. By learning from other projects and trying to understand the development process renovation concepts can be identified. However, it is argued that renovation is a wicked problem and therefore there is no generic solution that can be applied. Moreover, analyses regarding renovation concepts are uncertain; nevertheless, these analyses are still valuable for decision makers and represent the best attempts to assess the impact of renovation.

Key words: Renovation, Vertical extension, Financial viability, Environmental performance, Development process, Wicked problems

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MADE IN SWEDEN

To Arvid, Marie and my parents

Acknowledgements

Over the last five years, I have been on the journey of becoming a researcher, with the aim of completing and presenting this dissertation. The road has been tricky to navigate at times and occasionally I have taken a wrong turn. Nevertheless, I have enjoyed the journey and the company of my fellow researchers. The journey has been truly rewarding. As the end is approaching, I cannot help but to wonder what my next journey will be.

I want to thank my main supervisor Stefan Olander and my co-supervisor Henrik Szentes; as well as, my former main supervisor and our head of division Anne Landin for their support and guidance. Special thanks to Brian Atkin, Carlos Martínez-Avíla and Soheila Bahrami for their help and fruitful discussions. I also want to thank my other colleagues at the division of construction management, each and every one has in some way contributed to my research. Since the multi-active façade research project has contributed to my research significantly, I want to thank the research group members: the late Åke Blomsterberg, Ricardo Bernardo, Stephen Burke, Petter Wallentén and Suzanne Gosztonyi. I also want to thank my wife Marie and our son Arvid, as well as, mom, dad and my two brothers for their moral support.

Lund, April 2019

Rikard Sundling

Summary

In Sweden, housing accounts for about 23% of all energy consumption. Sweden wants to reach net zero carbon emissions by 2045; as such, it is likely that energy-reducing measures for housing will be needed. Many existing buildings have been in operation for 50 years or more and are therefore in need of modernisation. At the same time, the population is increasing and so is the rate of urbanisation, which is why there is, and will be for the foreseeable future, a need for more housing. Energy-efficient renovation and vertical extension of buildings are potential solutions to these three needs. In this dissertation, the financial and environmental effects, as well as relevant success factors for renovation are presented.

The research is based on three case studies. In the first, a building which was renovated to incorporate energy saving measures was assessed. It was only after completion of the work that the developer found that the renovation was not financially viable. In order to find a financially viable renovation option for the remaining buildings, which were very similar to the first, the developer chose to investigate if a renovation in combination with a vertical extension could increase revenues and thus justify renovation. A lifecycle profit analysis and a lifecycle impact assessment for four different renovation concepts were explored. The results of the analyses showed that the combination of energy-efficient renovation and vertical extension was the sole financially viable concept and also had the best environmental performance of the analysed concepts.

In the second case study, four different cases of vertical extensions were investigated, two which had been realised and two of which were still in the planning stage. The study showed that vertically extending buildings can be a complex undertaking. In order to motivate more property owners to realise more vertical extensions, a simplified development process based on a flow chart of success factors was developed. The intention was that the development process would contain the most important success factors, in a suggested order of decision making, so that vertical extensions could be more easily implemented.

The third case study deals with the financial viability of energy-efficient renovation concepts with a focus on prefabricated multi-active facades. Six different renovation concepts are presented, using prefabricated multi-active facades. Interestingly, the lifecycle profit analysis showed that for one of the

buildings, all concepts were financially viable; while for the other, no renovation concepts were viable. The results of the study also showed that small changes in regard to cost and price changes can significantly alter the results of lifecycle profit analyses.

Further findings from the studies revealed many fundamental challenges regarding renovation. Using *wicked problem* theory, one can re-interpret the results from an alternative perspective. For example, the first study showed that whether a renovation concept has high or low environmental performance depends on which environmental factors one chooses to assess. Since there are many stakeholders affected by renovation projects, a relevant and critical question could be: "Who has the right to decide which environmental factors are the most important to focus on?".

Overall, the studies reveal financially viable renovation concepts which can contribute to environmental performance. However, the analyses are sensitive and even small changes can alter the results; in addition, the actual outcome may differ from the results of the analysis, since the lifespan of the renovations are typically decades long. While describing the development process and success factors can ease project realisation, renovations are complex projects and their effects are not completely beneficial.

Sammanfattning

Bostäder står för ca 23% av all energianvändning i Sverige. Om målet netto-noll koldioxidutsläpp 2045 ska nås är det därför troligt att energibesparande åtgärder för bostäder kommer behövas. Många av de befintliga byggnaderna är runt 50 år eller äldre och är således i behov av modernisering. Samtidigt ökar urbaniseringstakten, därför finns det och kommer även framöver finnas behov av fler bostäder. Energieffektiv renovering och våningspåbyggnad skulle kunna bidra till att lösa dessa tre behov. I denna avhandling behandlas de finansiella och miljömässiga effekterna samt relevanta framgångsfaktorer för renovering.

Forskningen som presenteras här baseras på tre fallstudier. Fallstudie 1 handlar om en byggnad som blev renoverad, men först efter realisering visade det sig att renoveringen inte var lönsam. För att finna en ekonomisk försvarbar renovering av de fem andra byggnaderna, som var väldigt lika, valde fastighetsägaren att undersöka om renovering i kombination med våningspåbyggnad skulle kunna höja intäkterna och på så sätt motivera renovering. I studien redovisas en livscykelvinst analys och en livscykel konsekvensbedömning för fyra olika koncept. Resultaten från analyserna visar att kombinationen av renovering och våningspåbyggnad var det enda ekonomiskt försvarbara konceptet och hade bäst miljöprestanda av de koncept som analyserades.

I fallstudie 2 undersöktes fyra olika fall av våningspåbyggnader, både planerade och realiserade. Studien visar att våningspåbyggnader är komplexa, så för att motivera fler fastighetsägare till att göra fler våningspåbyggnader utvecklades därför en förenklad utvecklingsprocess, ett flödesschema av framgångsfaktorer. Syftet är att denna utvecklingsprocess ska innehålla de viktigaste framgångsfaktorerna, i den ordning som beslut bör fattas, så att en våningspåbyggnad lättare kan genomföras.

Fallstudie 3 handlar återigen om ekonomiskt försvarbara renoveringskoncept, men denna gång gällande prefabricerade multiaktiva fasader. I studien presenteras sex olika renoveringskoncept där prefabricerade multiaktiva fasader används. Intressant nog visar livscykelvinst analysen att för ena byggnaden är alla koncept är ekonomisk försvarbara, medan för den andra så är inga renoveringskoncept försvarbara. Resultatet från studien visar också att små ändringar i kostnader och prisförändringar kan påverka resultaten från livscykelvinst analyser signifikant.

Vad som inte presenteras i de individuella studierna utan är mer övergripande resultat, är de utmaningar som kan kopplas till renovering. Genom att använda *wicked problem* teori kan man vrida på resultaten från studierna för att se dem från ett alternativt perspektiv. Exempelvis så visar fallstudie 1 att huruvida ett renoveringskoncept har hög eller låg miljöprestanda beror på vilka miljöfaktorer man väljer att analysera. Eftersom det finns många intressenter som är inblandade i renoveringsprojekt skulle en relevant kritiserande fråga skulle därför kunna vara: ”Vem är det som har rätten att besluta om vilken/vilka miljöfaktorer som är viktigast att fokusera på?”.

Sammanfattningsvis indikerar dessa studier att det finns ekonomiskt försvarbara renoveringskoncept som kan bidra till en förbättrad miljöprestandan. Dock är analyserna känsliga för även små ändringar eftersom renoveringens livslängd typiskt är lång, så det faktiska utfallet kan märkvärt skilja sig från analysens resultat. Samtidigt som beskrivningar av utvecklingsprocessen och av framgångsfaktorer kan underlätta projektrealisering, så är renoveringar komplexa projekt och dess effekter är inte enbart fördelaktiga.

Table of Contents

1. Introduction

In this introduction, the background and problem statement are presented, followed by the aim and objectives, the research questions and research limitations. This chapter also includes the published contributions from the research and outlines the structure of the dissertation.

1.1 Background

The renovation of buildings can help to limit both greenhouse gas emissions and the need to modernise the existing building stock. This can be done in a number of ways, for example: energy-saving measures and vertical extension, which is the focus of this dissertation.

After the Second World War, the Swedish economy was on the rise but the housing stock was outdated. The aim of the *million homes programme* was to increase living standards and build more modern housing (Socialdepartementet, 1961; Inrikesdepartmentet, 1965). However, 50 years have passed since the start of the *million homes programme* and now most of these buildings are in need of renovation. Compared to modern buildings, they are especially energy inefficient (Energimyndigheten, 2017a). According to Mangold (2016), there is an accumulated need for renovation, since many buildings in Sweden are reaching 50 years of operation and about 60% of the building stock is in need of renovation. Buildings are one of the few asset types which are so valuable that merely maintaining and caring for them is not enough; thus, there is a need to renew and improve upon them. The purpose of a renovation is often to extend the lifespan of the building so that it can be used longer than was originally planned. A building which is being continuously renovated can be used far beyond the originally planned lifespan.

Many of the buildings that are about 50 years old are also suitable for vertical extension (Nilsson, 2017), since they typically have strong structural frameworks of concrete or loadbearing brickwork (Boverket, 2010). The vertical extension of buildings could address the increasing urban population (United Nations, 2017;

United Nations, 2018). The benefit of a vertical extension, compared to other densification efforts, is that the added apartments do not increase land use.

If climate change is to be addressed, there is a need to slow down the rate of change by reducing greenhouse gas emissions. In response, Sweden has set the target to reach net-zero greenhouse gas emissions by 2045 (Regeringskansliet, 2017; Regeringskansliet, 2016). According to the Swedish energy agency [Energimyndigheten] (2017b) the housing sector uses about 23% of all the energy in Sweden; thus, the renovation of residential buildings can potentially mean significant contributions to the 2045 goal. In a national study of 31 renovated buildings, Högdal (2013) showed that renovation, with a focus on energy-saving measures, could reduce energy use by anything between 30-82%.

However, Olsson et al. (2015) showed that it is financial, and not technical aspects, which are the main barriers concerning energy-efficient renovation. Additionally, the Swedish National Board of Housing, Building and Planning [Boverket], (2013) showed that while energy-efficient renovation is technically possible, it is more rarely financially viable. In a case study of low-energy buildings by Boverket (2015), it has been shown that it is not financially beneficial to decrease energy use in residential buildings below the building code requirements, even though energy-saving measures could mean significant reduction in greenhouse gas emissions. In two follow up studies to Högdal (2013), findings show that energy-efficient renovation can be financially viable; in Westerbjörk, (2015) it was shown that certain energy-saving measures are more financially viable than others. Later, in Westerbjörk, (2017), it was shown that eight out of the ten cases studied underwent financially viable renovations which led to energy reductions of 50% or more.

1.2 Problem statement

There seem to be renovation concepts which could be both financially viable and environmentally beneficial (Westerbjörk, 2015; Westerbjörk, 2017). If there is such potential, then one might reasonably expect the market to act and renovate more buildings. The accumulation of buildings in need of renovation (Mangold, 2016) suggests there might be other reasons. This opens up the possibility of renovation projects being more complex than assumed and that a lack of understanding of the development process might be at fault.

For example, older buildings in need of renovation, increased energy-efficiency could mean significant reductions in energy use (Högdal, 2013). Unfortunately, what these renovations mean in terms of environmental performance is not as often highlighted. Reduction in energy use could stimulate investment; however, studies have shown that while renovation projects are technically feasible, the financially viability of these projects are questionable (Boverket, 2013).

1.3 Aim and objectives of the research

The primary aim of this research was to study the implementation and the effects of building renovation. First, there was a need to identify and understand why renovation appears to be complex. Second, there is a need to define a development process for the purpose of renovation. In addition, there is a need to determine if renovated buildings can contribute to improved environmental performance. Finally, there is a need to examine if such renovations can be financially viable.

1.4 Research questions

The problem statement leads to four research questions.

RQ 1: How does complexity impact the success of renovation projects?

RQ 2: To what extent is it possible to define a development process for renovation projects?

RQ 3: To what extent is improved environmental performance possible through renovation?

RQ 4: To what extent can the financial viability of renovation projects be evaluated?

According to Alvesson and Sandberg (2013) formulating relevant research questions is an activity that is as valuable as searching for evidence, since finding good answers to a poor question is just as irrelevant as finding poor answers to a good question. Innovative research questions are required to generate interesting, validated and influential theories. The above research questions highlight four relevant aspects of renovation. On their own, they highlight the importance of detailed assessments of fundamental concepts and when combined they contribute with a more holistic overview of the challenges that this field is facing.

1.5 Limitations

In this research, two types of renovations have been assessed, energy-efficient renovation and vertical extension of buildings. There are indeed other types of renovations such as modernisation and interior remodelling; however, these fall outside the scope of this research, even though some aspects of renovation in general are highlighted. The renovation concepts investigated here focus on single multifamily residential buildings in cold climates. The environmental performance has been analysed using a lifecycle impact assessment of global warming potential, cumulative energy demand and non-renewable energy. While there are many other factors influencing environmental performance, these are out of scope for this research. The analyses presented in this dissertation are mainly focused on the buildings before and after renovation: the performance of the construction process has not been investigated.

1.6 Publications

1.6.1 Scientific papers appended to this dissertation

1. Enabling energy-efficient renovation: the case of vertical extension to buildings
   Published (2019) in Construction Innovation, Vol. 19 Issue: 1, pp.2-14
   Authors: Rikard Sundling, Åke Blomsterberg and Anne Landin

2. A development process for extending buildings vertically – based on a case study of four extended buildings
   Published (2019) in Construction Innovation
   Author: Rikard Sundling

3. Lifecycle profit analysis of prefabricated multi-active façades
   Published (2019) in International Journal of Building Pathology and Adaptation
   Authors: Rikard Sundling, Stefan Olander, Åke Blomsterberg, Petter Wallentén, Stephen Burke, Ricardo Bernardo

4. Why are we not renovating more?
   Manuscript to be submitted to Construction Management and Economics
   Author: Rikard Sundling and Henrik Szentes

Distribution of work

Tabel 1.1 The distribution of work for the papers

Paper	**Distribution of work**
Paper 1	Sundling is the main author, Blomsterberg and Landin supervised and reviewed the work. Blomsterberg also contributed in the empirical study.
Paper 2	Sundling is sole author.
Paper 3	Sundling is the main author, the other authors were part of the empirical study and have contributed to the writing of the paper.
Paper 4	Sundling is the main author, Szentes contributed to both the theory and the writing of the paper.

Links between the research questions and the papers

Tabel 1.2 The links between the research questions and the papers

Research question	**Paper**
How does complexity impact the success of renovation projects?	Paper 4
To what extent is it possible to define a development process for renovation projects?	Paper 2
To what extent is improved environmental performance possible through renovation?	Paper 1
How can the financial viability of renovation projects be evaluated?	Paper 1 and 3

1.6.2 Other publications

Conference papers

I. Renovation of a Multi-family Building in Sweden – Analyses of Energy Savings, LCC, LCA and Co-benefits
Presented at the 12th REHVA World Congress CLIMA 2016, 22-25 May, Aalborg, Denmark
Authors: Åke Blomsterberg and Rikard Nilsson [now Sundling]

II. Vertical Extension of Buildings as an Enabler of Energy Renovation
Presented at the 12th REHVA World Congress CLIMA 2016, 22-25 May, Aalborg, Denmark
Authors: Rikard Nilsson [now Sundling], Åke Blomsterberg and Anne Landin

III. An exploratory study of the practice of stakeholder participation in densification projects
Presented at the 20th CIB World Building Congress 2016, 30 May to 3 June, Tampere, Finland
Authors: Carlos Martinez-Avila, Rikard Nilsson [now Sundling], Stefan Olander and Anne Landin

IV. Prefabricated multi-active facade elements for energy renovation of multi-family houses – A theoretical case-study in Sweden
Presented at the 41st IAHS World Congress 2016, 13-16 September, Albufeira, Algarve, Portugal
Authors: Luis Ricardo Bernardo, Ahmed Hadzimuratovic, Markus Swedmark, Stephen Burke, Rikard Nilsson [now Sundling], Tomas Ekström, Susanne Gosztonyi, Åke Blomsterberg

Reports

V. Evaluation of the impact and relevance of different energy related renovation measures on selected case studies (Annex 56)
Published by University of Minho, Portugal, 2017
Authors: David Venus, Karl Höfler and others. Åke Blomsterberg and Rikard Nilsson [now Sundling] authored the Swedish case study.

VI. Förstudie av prefabricerade multiaktiva fasadelement för energirenovering av flerbostadshus
Published by SBUF, ID: 13105, 2018
Authors: Ricardo Bernardo, Åke Blomsterberg, Stephen Burke, Susanne Gosztonyi, Rikard Sundling, Petter Wallentén

VII. Prefabricerade fasadelement för renovering : Förstudie
Published by E2B2, Energimyndighetens projektnummer: 40797-1, 2018
Authors: Åke Blomsterberg, Stephen Burke, Rikard Sundling

Licentiate dissertation

VIII. Vertical extension of buildings (Licentiate thesis, Lund University, Lund)
Printed by Media-Tryck, Lund University, Lund, 2017
Author: Rikard Nilsson [now Sundling]

1.7 Structure of the dissertation

There are six chapters in this dissertation. In the first chapter, the background, the problem statement, aim and objectives, the research questions, limitations and publications are presented.

Chapter 2 presents the author's epistemological framework, the research process and theory on empirical studies. Additionally, the case study methodology, data gathering and methods for analysis are also presented. The chapter ends with a discussion on validation regarding the research.

In Chapter 3, the core theoretical concepts are presented, namely energy-efficient renovation, vertical extension of buildings, lifecycle impact assessment, lifecycle profit analysis and wicked problems.

Chapter 4 presents the three case studies and their findings. In case study 1, the combination of energy-efficient renovation and vertical extension is examined. Case study 2 explored the development process of vertically extended buildings. In case study 3, energy-efficient renovation concepts based on prefabricated multi-active façades were explored.

Chapter 5 consists of a discussion on the answers to the research questions. The purpose of the discussion is to combine the findings from the case studies with relevant literature.

The final conclusions of the research are presented in Chapter 6. In addition, the contributions of the research and suggestions for future research are also presented.

2. Research methodology

This chapter starts with the author's epistemological framework and the research process. Later, important aspects of empirical research are presented. Since the work presented in this dissertation is based on case study research, this method and its associated data gathering are also explained. Finally, a discussion regarding the validity of the research is presented.

2.1 Epistemological framework

Earlier, I would have defined myself as a positivist; that is, a researcher who would create theories and models of the world perceived through our senses (Pardi, 2015). According to Molander (1988), a positivist is a researcher who uses sensory experience and observations to derive information and through logical reasoning creates knowledge. In addition, a positivist rejects pseudoscience and metaphysics as they are not measurable or testable and therefore not worth studying. However, this presents a tricky problem for researchers, since much social science, for example, is hard to measure. How does one measure satisfaction or dissatisfaction with respect to a renovation project? A purely positivistic view would be that such aspects are not worth studying until they are measurable. While I still value the fundamental ideals of replicability and neutrality, which are essential for positivistic research, I do today consider myself more of a pragmatist. A pragmatist is a researcher who focuses more on the practical uses of the theory, rather than its theoretical contributions or whether it is considered correct or not; in addition, pragmatism can also be seen as a combination of positivism and interpretivism (Mitchell, 2018). Mixed methods research is suitable for a pragmatist according to Mitchell (2018), since such an approach can be used to maximise practical use, thus producing a likely and lovely explanation. As such, pragmatism relies heavily on abductive reasoning.

Abductive reasoning attempts to find explanations given available data. The goal is to understand the phenomenon and why it happened; the goal is not to deduce or prove anything (Persson and Sahlin, 2013). Therefore, an abductive researcher might not be interested in what is true or not, but rather what best explains the phenomenon; thus, embracing a more pragmatic approach. According to Alvesson and Kärreman (2011), both inductive and deductive reasoning require data and theory to be two separate entities; that is, data are independent of theory. Yet, certain data is supposed to *fit* certain theories. Alvesson and Kärreman (2011) disagree with this view; instead, they support the idea that data is shaped by our theories, understanding and personal values. Therefore, it is important to remain humble to the fact that our data is a reflection of ourselves. Moreover, Alvesson and Kärreman (2011) argue that in practice there is no inductive and deductive reasoning. Inductive reasoning expects the researcher to make conclusions based on observations, without any guesses or hypotheses (Persson and Sahlin, 2013); however, without knowledge and understanding the conclusions lack context. This, in turn, might lead to general and lacklustre conclusions, or worse, wrong conclusions if the number of observations is not high enough. Deductive reasoning on the other hand, expects the researcher to go through three steps: formulating a hypothesis, testing the hypothesis and then drawing conclusions. Even so, one cannot make a relevant and interesting hypothesis without having a good understanding of the phenomenon. Additionally, the conclusions need interpretation otherwise other researchers will struggle to find uses for them. This could of course be left for others to discover; however, as the researcher and designer of the test one probably has some of the best understanding of the phenomenon, thus personal interpretations might contribute the most. Nevertheless, any abductive explanation still to be has formulated so that it is logically compatible with available data (Persson and Sahlin, 2013).

2.2 Research process

The research comprises three case studies. Figure 2.1 shows when the case studies were conducted and approximately how much time was spent on each of them. When I started my doctoral studies, I was told by one of my colleagues that the technical solutions existed to reduce significantly the energy use of buildings and that the main challenge was to find financially viable renovation concepts. Thus, my research began with case study 1, which was focused on the energy-efficient renovation of a multifamily building. Later, it was revealed that the housing developer was also planning to vertically extend several similar buildings, so these extended buildings were therefore included in the study. Some of the findings from case study 1 suggested that implementing vertical-extension projects was a complex affair; therefore, I wanted to investigate this aspect in case study 2. This second study consisted of four cases of buildings which were either planned to be vertically extended or had already been extended: the extended buildings from case study 1 were part of this study. Since vertical extensions had been a significant part of my work at that point, my licentiate dissertation was appropriately entitled “Vertical extension of buildings”. During the writing of my licentiate dissertation, a new research project about multi-active façades was initiated and this brought me back to the financial evaluation of renovation concepts. My contribution and my supervisor’s contribution to the research project are summarised in case study 3. The multi-active façades research project finished recently and since then I have focused mainly on publishing my work and writing this dissertation.

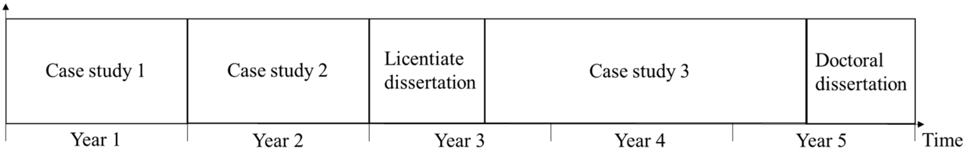


Figure 2.1 The three case studies over time.

The typical research process used for the case studies in this research consisted of five steps: problem identification; literature review; case study; results and analysis; and reporting. Figure 2.2 illustrates this process. Problem identification might have come from a variety of sources, for example literature searches, meetings, interviews or discussions with other researchers. Once the problem has been identified, there was a need to understand the nature of the problem and how, or if, it had been tackled previously, before a study could be designed. This is typically done through a literature review, the aim of which is to define the problem and learn from other studies related to the problem. The first two steps usually generate an understanding of the gaps related to the problem. The third step is to perform an empirical study which should be designed to examine one or several of these gaps. Once the study has been carried out, the results from the study can be analysed and conclusions can be drawn. Finally, the study and especially the conclusions are presented in a report, so that others might learn from the study or replicate it.

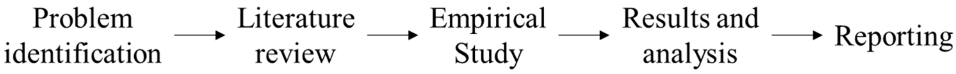


Figure 2.2 The research process for the case studies.

As mentioned earlier, three case studies underpin this dissertation, where the research strategy, data gathering methods and analysis methods are presented in table 2.1; in addition, the contribution of each study to the papers is noted. The case studies and the findings are described in chapter 4 and the full-length papers can be found in the appendix.

Table 2.1 The three case studies conducted as part of the research.

	Case study 1	Case study 2	Case study 3
Research approach	Abductive	Abductive	Abductive
Data gathering methods	Document analysis, site visits and interviews.	Interviews, document analysis, and site visits.	Model assessment, industry data gathering and reference group discussions.
Analysis method	Computer-based simulations	Data-driven coding	Computer-based simulations
Papers	Papers 1 and 4	Papers 2 and 4	Papers 3 and 4

Verification

All research must be verified in some way. The verification process includes assessing the empirical data but also the methods used to gather the data (Fellows and Liu, 2008). As such, research must be presented in such a way that other researchers can review and replicate the studies. This research has been verified through publication of the results in scientific journals, where the papers have been subject to double-blind peer review. The research in case studies 1 and 3 has also been verified by the collaborating researchers and experts in the field. Case study 1 was undertaken in collaboration with the contributing members of IEA-EBC Annex 56 and was, as such, continuously assessed by the members. Case study 3 has been verified by the funding agencies and a reference group.

Reliability

Reliability is linked to the replicability of the research; in other words, how reliable the results are compared to similar or replicated studies (Fellows and Liu, 2008). Due to the project-based nature of the construction industry, each project is unique to a greater or lesser extent, making studies of these projects more challenging to replicate. Therefore, it is essential that the methods used in the study are explained in detail. If several studies were used to assess the same phenomenon using the same methods, it would be possible to determine the variance between the studies and potentially identify measurement error (Fellows and Liu, 2008); however, this falls outside the scope of this research.

2.3 Empirical studies

Alvesson and Sandberg (2013) argue that one should not assume that good research spontaneously arises from empirical work. According to Feenberg (2017), there is a problem regarding how much trust can be put on empirical evidence. The problem Feenberg (2017) highlights is that even if experts are being critical and basing their critique on relevant experience and knowledge, contradicting empirical data still has a cultural advantage. Feenberg's rationale is that, in the scientific community, empirical data is currently more valued than experience, even when the empirical data might be just as, or even more, biased. Empirical work should be both challenging and interesting; therefore, one should plan and think about the empirical work before engaging with it.

It is generally accepted that the researcher should avoid being biased in research overall. The researcher should try to *defamiliarise* or distance oneself from the research and especially from the empirical study. In this sense, the researcher should try to be as Persson and Sahlin (2013) describe with respect to inductive research, which is that one should approach the phenomenon like a child, with curosity and without prejudice. The aim of defamiliarisation is to study the phenomenon without bias so that the data is not intrepreted before empirical work is over. It might seem easy; however, Alvesson and Kärreman (2011) highlighted the difficulty of such a research process. As researchers, we are part of the culture, norms and traditions that exist in our respective fields; and so, it is extremely challenging to distance oneself from the empirical work.

During the empirical work it is also relevant to *problematise*, the act of unravelling or deconstructing a phenomenon (Alvesson and Kärreman, 2011). The propose of problematisation is to deconstruct and to delve deeper into the building blocks of the phenomenon, in order to find data that can be reconstructed to fit several alternative narratives, not one single narrative. One of the three Socratic perspectives is *knowledge stability*; that is, to be aware of what we know and what we do not know (Persson and Sahlin, 2013). The art of problematising and deconstructing phenomena and arguments is key for exploring the limits of your knowledge. This can also be linked to deductive thinking, where the researcher can test one specific aspect of the phenomenon in an experiment (Persson and Sahlin, 2013). This experiment will either validate or falsify the specific aspect and this newly learnt knowledge can then perhaps be used to formulate a new narrative.

According to Alvesson and Kärreman (2011) different interpretive repertoires will cast empirical observations in different lights. This could potentially contribute to a wider understanding and increase knowledge of a phenomenon. Therefore, a researcher can develop and maintain several interpretive repertoires in order to interpret data through different perspectives. To do so, the researcher must first master a few different research fields, or at least get to know them to such a level that the researcher can understand and make minor contributions to the field. The researcher must also be able to address relevant topics and perceive the world from the perspective of the community in question. Moreover, the researcher needs to be aware of any changes and breakthroughs in the field. Different interpretive repertoires will also reveal that there is no ultimate truth, instead there is only differently interpreted information. No matter how much data there is supporting a theory, sooner or later that theory will fall or be reworked; this is also consistent with the Socratic principle *knowledge stability* (Persson and Sahlin, 2013).

Research should also include *reflexive critique*, which is the art of critically reviewing your own research. Alvesson and Kärreman (2011) highlight several topics which can be part of a reflexive critique. Language is always changing and adapting; therefore, we should not assume that one word can accurately describe a phenomenon. Instead, one must accept that there might be other words which have similar meaning or that other words can be used to describe the phenomenon. It is also worth keeping in mind that you do not own or control the words you use; instead, your words might be used for something else by others in the future. Additionally, a written text is always flawed in some way. Other researchers might derive different conclusions from what you thought you were depicting. *Reflexive critique* is linked to the Socratic principle of *fallibility* about which we, as researchers, should be aware of our own fallibility in that our beliefs and biases do to some extent affect our research.

2.4 Case study research

According to Yin (2014), a case study is the study of a phenomenon in its real-life context. A case study thus takes into account the context surrounding the phenomenon. Whereas other types of research emphasise the isolation and separation of phenomenon and contexts, it is an integral part of case study research. A detailed study of a single case can therefore provide in-depth understanding of a phenomenon and its context. According to Stake (2013), a case study based on multiple cases allows for the study of similarities and differences; it also offers opportunities to learn about complexity and context. Thus, a multiple case study can provide comparisons between cases and contexts where a phenomenon exists.

Moreover, case study research can include both qualitative and quantitative data gathering methods. According to Holme and Solvang (1997), the aim of qualitative methods are to develop a better understanding of a phenomenon;

whereas, the purpose of quantitative study is to strengthen or undermine theories. The results from qualitative data gathering can often be presented as explanatory text and the results from quantitative data gathering can typically be illustrated in figures and numbers. Qualitative methods usually rely on the researcher to interpret the results, while quantitative methods generate statistical data which is easier to replicate. According to Fellows and Liu (2008), a case study is typically based on a mix of data gathering methods such as interviews, observations and documents. Unlike a survey, study based on for example questionnaires where the aim is to reach statistical significance, a case study is aimed at finding deep and narrow data regarding a phenomenon.

As can be seen in table 2.1, the main method used in this research is case studies. The first is a study of four renovation concepts, two of which have been realised, and all of which were related to one building. The second is a study of four buildings which have been vertically extended. The final study is that of seven renovation concepts, based on two buildings.

2.5 Data gathering methods

Interviews

Interviews are a flexible method for data gathering and are especially well suited for learning from industry about current practice or current challenges. Interviews are flexible compared to experiments, which can offer little flexibility regarding their planning and execution (Alvesson, 2011). This flexibility does, however, lie in the ability to make improvements to the interview guide and execution during the course of an interview series. Additionally, one could even make changes during an interview if the researcher identifies other topics of interest or the interviewee presents an interesting opinion. However, interviews are also flexible in the sense that it is up to the researcher to interpret the results, which can introduce bias. It should also be noted that interviews are an interactive method, thus, allowing both the interviewer and the interviewee to ask questions, seek clarification and learn from the interaction.

The interviews which were undertaken during this research were mainly single participant semi-structured interviews. There are three types of interview: structured, semi-structured and unstructured interviews (Fellows and Liu, 2008). A structured interview is well suited for an interviewer who is searching for answers to specific questions; usually, these questions are carefully thought through, planned and written down before the interview. A structured interview is therefore similar in some respects to questionnaires. On the other side of the spectrum, an unstructured interview is more like a monologue, where the interviewer introduces a topic and then lets the interviewee freely talk about that topic. The goal of an unstructured interview is to allow the interviewee to share his or her experience and knowledge regarding a specific topic. Semi-structured interviews represent the spectrum between these two types. As such, a semi-structured interview is typically partly structured and partly unstructured.

As seen in table 2.1, the data gathering methods used in case study 3 includes reference group discussions. Fellows and Liu (2008) noted that there are two types of group interview methods: the Delphi method and the focus group method. The reference group discussions could best be described as adopting the focus group method, where the aim is to explore opinions, judgement and evaluations from experts in a field regarding a specific topic.

Document analysis

Documents are a means of storing and sharing information and knowledge of an event. There are a plethora of documents relevant for researchers in the field of construction, such as: design drawings, models, procurement documents and feasibility studies. Since documentation is a means for storing information, a document might contain more information than is possible to gather from interviews, for example. Nonetheless, according to Fellows and Liu (2008), documents cannot be regarded as "independent facts" since they are reflections of their writers. Documents are affected by factors such as the writer's political view, the mother organisation's public policy and the writer's experience of the event. There is therefore a need for the researcher to understand the wider context of the documents being examined. It should also be noted that the researcher also interprets a document with respect to his or her own background.

Site visits

Site visits are a type of observation in which the researcher travels to a location where a phenomenon is taking place to observe it. Observation introduces bias since it is the researcher who is responsible for selecting which things to observe (Fellows and Liu, 2008). The site visit observations can, similarly to interviews, be structured or unstructured; either one plans before visiting the location which aspects are worth observing or observe whatever one might find interesting once at the site.

2.6 Methods for analysis

Computer-based simulations

In this research three characteristics of reality have been simulated by computer; they are energy use, lifecycle impact and lifecycle profit. Simulations are made to represent essential characteristics of reality (Fellows and Liu, 2008). The benefit of simulations, compared to experiments, is that they can be used in a theoretical sense to assess the effects of a specific measure, without having to deal with these effects in reality. In addition, simulations can be used when the cost of performing an experiment is too high or the experiment is too complicated. However, the results from a simulation are never certain, since the model is merely a simplified representation of reality. Finding simulation software which has been validated is essential. In addition, it is necessary for the researcher to be aware of the underlying methodology used by the software. At the heart of every simulation is a model with inputs for the simulation; thus, realistic simulation results require precise input data. Any inaccuracies in either the software or the input data will adversely affect the results. Furthermore, simulation inputs are typically mostly based on earlier events and should therefore not be interpreted as what actually will happen in the future; instead they should be interpreted as what is likely to happen given historical data.

The energy use in case study 1 was simulated using *VIP-Energy* (StruSoft AB, 2016a). *VIP-Energy* is software which calculates the energy use of buildings with respect to heating, climate, ventilation and user behaviour. The software has been validated against both ASHRAE 140-2007 and EN 15265-2007 (StruSoft AB, 2016b). The energy use in case study 3 was simulated using *IDA Indoor Climate and Energy* (EQUA Simulation AB, 2019) which, as in the case of *VIP-Energy*, is a dynamic simulation tool that can be used to calculate the energy use of buildings. The software has been validated by Kropf and Zweifel (2001) and Moosberger (2007). It should be noted that I did not design the models or perform any of the simulations, as this was done by my colleagues. I did, however, question their results, assisted in input identification and method design.

The lifecycle impact assessment covering global warming potential, cumulative energy demand and non-renewable energy was simulated using *Eco-Bat 4.0* (Eco-Bat, 2016). *Eco-Bat 4.0* is software which can be used to analyse the lifecycle impact of construction projects in general. The *Eco-Bat 4.0* software is compliant with ISO 14040:2006, SIA 2032:2010 and Minergie ECO standards (Eco-Bat, 2016). More than 140 materials and six categories of energy consumption can be taken into account while using this software. However, Eco-Bat 4.0 is no longer being updated, the software was replaced by Eco-Sai a few years ago.

Contrary to both the energy use and lifecycle impact simulations, the lifecycle profit analyses were simulated using two different spreadsheets, based on *Excel*.

Data-driven coding

Data-driven coding allows the researcher to find patterns amongst different cases and from them derive conclusions (Kvale and Brinkmann, 2009). Data-driven coding is a bottom-up approach, where the data from each case is highlighted as codes. The codes are compared and linked, with groups of connected codes formed into categories. Similarly, several connected categories can then form themes. Using this bottom-up ‘pyramid’ approach, the researcher can then explain how the different data support certain themes and refer to the data from the cases when presenting the findings. This method is well suited to inductive research since the data gathered in such studies are typically numerous and varied (Persson and Sahlin, 2013). However, construction projects are temporary, unique and often large in scale; thus, making it challenging to gather enough observations. A small number of observations will limit the conclusions that can be made, as well as limiting potential generalisations. Case study 2 is based on data which was gathered from interviews, documents and site visits for four cases of vertically extended buildings. This data was then structured in four steps: data (bottom), codes (lower middle), categories (higher middle) and themes (top) (see figure 2.3). The themes in this study were also structured into a development process, which is a proposed structure, or step-by-step guide, for implementing a vertical extension.

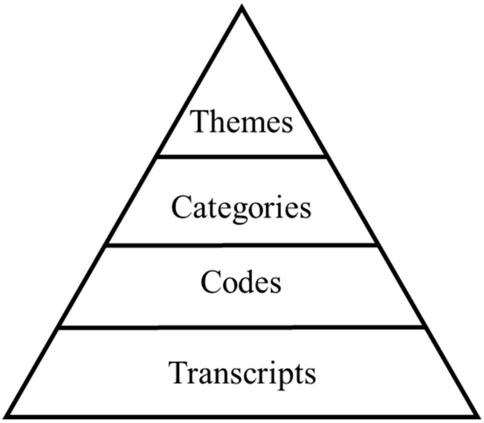


Figure 2.3 The pyramid structure of the results from case study 2.

2.7 Validation discussion

2.7.1 Research methods

As mentioned earlier, there are a few flaws which are unavoidable when using simulations. First, simulations are a simplified representation of reality and can therefore never provide exact output. Second, input for the simulation is usually based on historical data and not what will happen in the future. Moreover, input can also be based on assumptions which might be incorrect. Finally, any inaccuracies in either the simulation or the input data might cause further error. When these flaws are combined, the output of the simulation can be quite uncertain. In their study of lifecycle embodied energy, Rauf and Crawford (2015) identified an error range in their results of ±42%, a number which clearly shows the complexity of making long-term prognoses. Burke et al. (2017) showed that varying 16 parameters within realistic distributions in 1000 energy use simulations resulted in total annual energy use in the range of 40kWh/m^2 to 80kWh/m^2. This complexity is also highlighted in Chapter 4.4.2 *other findings not reported in attached publications*, where it is noted that just a small change in the inputs can have significant consequences for the results. One could therefore argue that long-term prognoses are limited and should not be used as the sole basis for decision-making. However, the purpose of lifecycle analyses is to provide depth and understanding of the available options. The outputs are not meant to be regarded as facts: one has to understand that reality is different from a prognosis. Moreover, understanding the effect of changes in key inputs on the results, as a form of sensitivity analysis, can provide valuable insights into the performance of different concepts. The alternative would simply be to guess what renovation concept would be best and that would not do. Thorough analyses are necessary because they increase knowledge and understanding of the available decisions; thus, even if the results of the simulation are flawed and are unlikely to realise, the knowledge and insights gained are valuable.

2.7.2 Case studies

Case study 1

One of the difficulties with case study 1 is that it could be argued that even a minimalistic renovation concept should offer some sort of energy reduction. For example, new windows, even with low U-values, could probably reduce energy use compared to the 50-year-old windows in the building. Additionally, concepts focused more on minor improvements, such as improved windows and the installation of a heat pump, would be interesting to study and compare to the other concepts presented in case study 1.

The rent for both the minimalist and the code-compliant renovation concepts were based on best estimates; however, it could be argued that the user value is the same for all concepts and so there should be similar rent changes for all concepts. In their description of user value, Hyresnämnden (2017) does not highlight any effects of energy-efficient renovation, such as thermal comfort, as noteworthy when determining user value.

Case study 2

The purpose of case study 2 was to use innovation theory as a means to establish vertical extension of buildings as an innovation and contribute to the diffusion of this innovation. Vertical extension of buildings is an innovation in its early stages, with some early adopters. For example, in a national report of 31 studied renovation concepts, only one of the concepts included a vertical extension (Högdal, 2013). Even though vertical extension of buildings does have a niche to fill, "take-off" in the market has yet to occur. According to Rogers (1995) diffusion of innovation is the process by which an innovation is communicated through certain channels over time among the members of a social system. Case study 2 contributed to the diffusion of vertical extension of buildings by focusing on the innovation-decision process. This is accomplished by sharing the *knowledge* gained from studying the four cases and creating a development process so that the *decisions* regarding the implementation of vertical extensions can be simplified. This would enable more developers to determine if the vertical extension of buildings can be implemented.

As highlighted by Davidson (2013), case studies can sometimes fail to capture the subtleties of the innovations, especially if the cases are researched from outside. The development process is based on all identified success factors from the four cases and literature on the topic; in other words, the process could likely contribute to further implementation of vertical extensions. Even so, the development process is probably not optimal and will need further development.

Case study 3

The simulations undertaken in case study 3 pose significant validation concerns since no realised renovation concepts were assessed. The study was thus considered theoretical. However, the data used to create and simulate these theoretical concepts were gathered from the industry. Several interesting approaches were assessed. Different insulation materials, methods for prefabrication and ventilation methods were compared and eliminated in reference group discussions, forming the six renovation concepts examined in the case study. The inputs for the lifecycle profit analysis were then gathered from energy simulations, construction cost simulations and companies in the industry. Yet, while the energy simulation software used in the study has been certified, the construction cost software had not; therefore, there was no way of knowing if the construction costs were realistic or not. As a result, the outputs from the analysis are rather uncertain. Since it was a pre-study, some uncertainty was expected.

3. Literature review

In this chapter, the five theories are presented. Figure 3.1 shows the five theories and in the categories which they fall under. This chapter begins with a description of energy-efficient renovation and vertical extension. This is then followed by theory on lifecycle impact assessment and lifecycle profit analysis. Finally, theory on wicked problems is presented.

Type of renovation	Methods for evaluation	Theory on complexity
• Energy-efficient renovation • Vertical extension of buildings	• Lifecycle impact assessment • Lifecycle profit analysis	• Wicked problems

Figure 3.1 The research fields linked to renovation which are presented in this chapter.

3.1 Energy-efficient renovation

As new and more efficient technologies are developed, more of the existing building stock can decrease its energy use by implementing these energy-saving measures. For example, in a national study of 31 renovated buildings, Högdal (2013) showed that energy-efficient renovation could reduce energy use by anything between 30-82%.

However, such measures have struggle to reach financial viability. For example in a study by Keoleian et al. (2000), the lifecycle energy use and costs for single-family houses in USA was assessed and it was concluded that energy reductions of 60% were possible; however, such a renovation would resulted in pay-back period of about 50 years, or longer if energy prices did not increase. In order to find financially viable renovation concepts, Amstalden et al. (2007) analysed energy-efficient renovations in Switzerland; their study showed that many energy-efficient renovation concepts were close to being financially viable. Moreover, Boverket (2013) showed that energy-efficient renovations which exceeded the building code requirements, in terms of energy use, struggled to reach financial viability. In order to identify viable renovation concepts and to study the effects of large-scale renovations, a technical procurement exercise was carried out where eight façade systems were identified (Mjörnell and Blomsterberg, 2014); however, the financial viability of these systems were still not sufficient enough for most developers. As such, the International Energy Agency [IEA] (2011) has identified that financial viability is one barriers for reducing energy usage in buildings, this is mainly because of high acquisition costs. In order to avoid the high investment costs, Nieboer (2017) highlights that most non-profit housing associations in the Netherlands chose to combine energy-saving measures and preventive maintenance, as well as implementing energy-saving measures in small steps. However, Nieboer (2017) also identified that those two approaches are not suitable for any large-scale renovations. Gustafsson et al. (2016) concluded that adding additional insulation in the building envelope did increase environmental performance; but did not contribute any particular financial benefits. Högdal (2013) concluded that there are three factor which affect how likely it is that a building is going to undergo energy-efficient renovation: type of owner, demography and energy performance. Owners with long-term perspective, such as municipal housing companies, are more willing to invest in energy-saving measures. Cities with populations larger than 140 000 have a higher demand for housing, which increases the willingness to pay more rent. Buildings with high energy use are easier to renovate, due to their low energy performance.

Since there is a problem finding financially viable renovation concepts, research on prefabricated solutions have lately been on the rise. For example, in the IEA research project, EBC Annex 50 “Prefabricated Systems for Low Energy Building Renewal” (Zimmermann, 2012), several realised concepts are presented. One of the reasons why prefabrication could be promising from a financial standpoint, is that many energy-efficient renovation concepts require residents to relocate since the construction work typically includes the installation of ducts for ventilation and heat recovery, as well as new windows for each apartment. One example of prefabricated façades from Austria, shows how the heating systems and photovoltaic systems can be integrated into the facades (Höfler, 2012; Blomsterberg, 2012). This means that construction time can be significantly reduced with a prefabricated façade system and that the residents can remain in the building throughout the construction work. According to Sousa (2013), approximately 22 percent of the existing housing stock in Portugal could be renovated using prefabricated façade elements. On a similar note, Paiho et al. (2015) argued that the existing housing stock in Russia and Finland also are suitable for renovation using prefabricated façade elements.

3.2 Vertical extension of buildings

3.2.1 Densification

At the end of the 19th century, the idea of garden cities was presented by Howard (2001). The purpose of the garden city was to providing a healthier living environment by providing residents with a smaller, self-sustaining and calmer city than the large, unhealthy cities of his time. However, as population increased and cars became more common after the Second World War, the garden cities instead developed into low-density urban sprawl. Frumkin (2002) highlight the health problems caused by urban sprawl, most of which are linked to car dependence. This car dependency leads to air pollution, urban heating, reduced physical activity and automobile-related morbidity and mortality (Frumkin, et al. 2004). On a similar note, Ewing et al. (2014) found that obesity and chronic diseases are less common among countries with higher density cities. The European Environment Agency (EEA, 2006) even claims that urban sprawl also threatens the very culture of Europe.

In order to reduce urban sprawl, efforts to densify the existing urban environment have been gaining momentum; for example, the three largest cities in Sweden each have their own densification plans (Regionplanekontoret, 2009; Göteborgs Stad, 2014; Malmö stad, 2010). According to Nabielek (2011), research by the Netherlands Environmental Assessment Agency has shown that densification can increase economic productivity, the emergence of new jobs and reduced ethnic and socio-economic segregation. Additionally, Nabielek (2011) argues that densification will continue to be necessary, since cities are dynamic and have to change as the needs of the population change. Moreover, a well-planned and effectively managed dense city can limit greenhouse gas emissions (Dogman, 2009). Similarly, Senbel and Church (2011) argue that suburban development produces higher carbon emissions than compact and mixed-use development with access to public transport.

However, Dogman (2009) also highlight that densification on its own does not lead to better development, careful planning is needed. Turok (2011) supports this argument, and argues that densification projects might have far-reaching socio-economic changes which are not always considered. Similarly, Quastel et al. (2012) showed that densification might also lead to gentrification and claim that there is a class-based dimension to densification. In an effort to increase public opinion regarding densification, the policy makers in Vancouver, Canada, initiated the EcoDensity planning effort which tied sustainability, affordability and liveability to densification (Rosol, 2013); however, the links between densification and sustainability were questioned by the opposition, which instead led to a lack of consensus among the public. In contrast, Kyttä et al. (2013) showed that residents in denser urban areas are generally more open to densification compared to people in less dense areas.

3.2.2 Vertical extensions

Even though the vertical extension of buildings is a type of densification it does not occupy recreational or public space and might therefore be considered when such space is at a premium. Additionally, the vertical extension of a building can be combined with renovation, and thus both provide additional housing and extend the lifespan of the building. In a study by Cukovic-Ignjatovic and Ignjatovic (2006), the results suggested that a lateral plus vertical extension in combination with an energy-efficient renovation would provide the best financial outcome. In another study, Jovanović-Popović et al. (2006) claim that it was possible to finance the renovation by performing a vertical extension of the building and then sell the added apartments. However, no analysis or data were presented in these two papers to support the claims.

According to Rogers (1995), innovation often starts off slowly, gaining a few early adopters. If there is a niche to fill and the innovation proves successful the innovation can reach its “take-off” stage. The vertical extension of buildings could be argue to not have reached its “take-off” stage yet, since there are still many opportunities for further implementation. In order to support the diffusion of innovation, success factors can be identified which simplifies project planning. There are two seminal publications on the success factors regarding the vertical extension of buildings. The first was published almost 40 years ago by Bergenudd (1981). In his doctoral dissertation he presents a checklist, which was based on a detailed case study; the checklist highlight seven topics: urban planning and regulations, supplementary functions, structural frame, building services installations, finance, construction management and design. Additionally, Bergenudd (1981) argues that vertical extensions increase the efficiency of existing infrastructure and that the vertical extension of buildings can lead to energy reductions. The second is an interview-based report by Lidgren and Widerberg (2010), who identified six success factors for the vertical extension of buildings: demand for housing; alternative forms of investment; architect involvement in the early stages; make inventory of the existing building; prefabricated elements; and resident involvement.

3.3 Lifecycle impact assessment

Climate change might lead to seriously negative effects, The effects of climate change include drought (Allen et al., 2010), sea level rise (Nicholls and Cazenave, 2010), increased power of storms (Hansen, et al., 2016) and more. While it is yet unknown exactly how impactful these negative effects will be, it is certain that they need to be limited. Since the driver for climate change is global warming induced by greenhouse gases, policy makers are setting goals to significantly reduce the emission of these gases (see for example Regeringskansliet, 2017). There is therefore a need to measure the how these gases can be reduced through energy-efficient renovation.

Lifecycle impact assessment (commonly called LCA, short for lifecycle assessment) is an approach used to analyse environmental performance of a product or process. The purpose of a lifecycle impact assessment is to estimate all of the emissions, energy and water use, wastes and other releases related to a specific product or process (Crawford, 2011). In order to fulfil this purpose, a lifecycle impact assessment has to account for all releases that occur during the whole service life of the product or process in question. In IEA EBC Annex 56 Ott et al. (2014) developed a methodology to assess the environmental performance of energy-efficient renovation. In this methodology, the four life stages of a building are taken into consideration: materials production, construction, operation and end of life. With regards to the renovation of a building, the following sources are of significant importance and should therefore be included (Ott et al., 2014): embodied energy use for all renovation measures, on-site energy generation and repairs, operational energy use and energy use for appliances. The results from this type of assessment can be used by developers to reduce the long-term environmental performance of their facilities, Crawford (2011) highlights two specific uses for the results from a lifecycle impact assessment; first, to compare the environmental performance of different products and processes in order to find the most environmentally beneficial option; second, to identify areas of improvement considering the environmental performance of a product or a process.

However, Ayres (1995) argue that lifecycle impact assessments might negatively influence the decision-making process if the underlying data are flawed; since, the results of a lifecycle impact assessments can never be better than what the inputs permit. Similarly, to lifecycle financial analyses, lifecycle environmental assessments are also a type of prognoses of long-term effects, and thus have some similar flaws. Ayres (1995) highlight that results derived from simulations and testing facilities might not translate into practice. On a similar note, Ott et al. (2014) argues that lifecycle environmental assessments are not easily applied in practice, as there is usually a lack of information, time and resources which undermines the assessment. Moreover, Aktas and Bilec (2012) argue that choosing an arbitrary calculation period for renovation concepts introduces a noteworthy amount of error into residential building lifecycle impact. Accordingly, Crawford (2011) highlights that the results of a lifecycle impact assessment are only indicative. Even so, there are no generally accepted methods for translating one environmental performance factor to another (Crawford, 2011). This is unlike financial analyses which only focus on one factor, money; whereas, an environmental assessment can include a plethora of factors such as: greenhouse gases, non-renewable energy and biodiversity.

Studies have shown that energy-efficient renovation of buildings can increase environmental performance significantly. For example, Itard and Klunder (2007) showed that renovating buildings instead of demolishing them uses about 40-60% less embodied materials, depending on the building and its lifespan. Gustafsson et al. (2016) demonstrated that energy-efficient renovation of multi-family buildings in Sweden could reduce primary energy by 58%, greenhouse gas emissions by 65% and non-renewable energy by 56%. Rauf and Crawford (2015) show that renovations which have long lifespans can have a considerable effect on the environmental performance of a building; while most lifecycle embodied energy is saved in the first 50 years of operation, a 29% reduction in life cycle embodied energy was found by comparing the service life between 50 to 150 years. These findings indicate the importance of identifying renovation concepts which maximises the service life of the buildings.

3.4 Lifecycle profit analysis

One of the simplest methods for assessing financial viability is the payback period method. The payback period method is a tool for calculating the amount of years it takes for an investment to reach a break-even point; in other words, the number of years of operations until the sum of net cash flow exceeds the acquisition cost. The benefits of the payback period method are that it is simple to use and works decently when the payback period is short. The problems is that this method does not take into account the costs of teeing capital to an asset; so if the payback period is long, say more than 20 years or so, then it is unlikely that the investment will meet the required rate of return, e.g. Lind (2014). Additionally, the method does not either take into account the lifespan of the asset. Thus, projects which generate long-term value, such as renovations, might be overlooked.

Another common method for estimating the financial viability is lifecycle costing. The lifecycle cost of an assets embraces all costs associated with it (Logistics management institute, 1965). The lifecycle cost takes into all costs from idea to elimination, including: feasibility studies, research, design, production, operation, maintenance and recycling. The benefit of the lifecycle cost method compared to the payback period method is that it does also take into account the lifespan of the asset and the capital costs.

Basically, the lifecycle cost method calculates the net present value of all the costs associated with one asset. When several renovation measures have been assessed this way, then the net present value of the costs can be compared. The equation for calculating the lifecycle cost (e.g. Davis Langdon, 2007) can be seen in equation 3.1.

$$NPV = \sum_{t=1}^{\mathrm{T}} \left(\frac{C_t}{(1+r)^t}\right) \tag{3.1}$$

NPV = net present value
C_t = costs year t
r = discount rate
T = the analysis period

As mentioned earlier the lifecycle cost method is focused on the costs associated with an asset; therefore by definition, this method does not take into account any income generated by that asset. Nor does it take into account the residual value of the asset after the lifespan is over. Regarding whether the residual value is relevant for renovation project is up for debate, some renovation measures such as façade insulation might last much longer than for example a heat pump. A method which takes both income and residual value into account is the lifecycle profit analysis, which builds on the lifecycle cost method. The equation for calculating the lifecycle profit (e.g. Bejrum, 1991) can be seen in equation 3.2.

$$NPV = -\mathrm{A} + \frac{R_T}{(1+r)^T} + \sum_{t=1}^{\mathrm{T}} \left(\frac{I_t - C_t}{(1+r)^t}\right) \tag{3.2}$$

NPV = net present value
I_t = income year t
C_t = costs year t
r = discount rate
T = the analysis period
A = acquisition cost
R_T = residual value at the end of the analysis period

The lifecycle profit method is in general similar to a cash flow analysis, but instead of assessing the whole building before and after renovation, the lifecycle profit method can isolate the renovation and thus be used to more easily compare different renovation concepts to each other.

Additionally, both the lifecycle cost and lifecycle profit methods are flexible enough to introduce more factors to the equation. In paper 3, for example we added the price changes to the lifecycle profit equation. Obviously, other factors could also be added so that the methods encompass all relevant factors for the financial evaluation of an asset.

However, the more factors one adds to the financial evaluation the more likely it is that the result will be flawed. A more complex method for evaluation introduces risks of failure in execution, simply put using the equation wrong. Another problem is that the more factors which are introduced the more likely it is that one of them are wrong, thus resulting in misleading output. A third problem is that one might not know what the output means; for example with regards to both lifecycle costing and profit the output is a number which is hard to interpret. This is why researchers such as Gluch and Baumann (2004) argue that the financial evaluation using lifecycle methods is inherently complicated. According to them lifecycle methods' practical usefulness is constrained by their oversimplification to monetary units, the lack of reliable data, complexity of the building process and conceptual confusions. Researchers such as Ludvig (2013) therefore propose that of life cycle evaluations can serve as a pedagogical and rhetorical tool for understanding the life cycle perspective of a building, but should not be the sole determining factor in decision making. Since, life cycle methods largely depended upon the quality of the information and data about the buildings, Crosbie et al. (2011) argues that these methods can be strengthened through the decrease uncertainty regarding the information and data. Crosbie et al. (2011) highlight four steps for this process: identify and model design alternatives, conduct building assessments, check design compliance and conduct trade off.

3.5 Wicked problems

According to Rittel and Webber (1973) a wicked problem is a problem which is impossible to truly solve since the problem develops as solutions are attempted. One of the reasons why it is impossible to solve is because wicked problems are systemic, they are intricate parts of society, and therefore lack definable boundaries. According to Hulme (2009), climate change is a typical wicked problem, sometimes even called a super wicked problem (Lazarus, 2008). This is because there are many interests which are at play, and the wickedness arises from the many clashes between these interests.

The opposite of a wicked problem, is a tame problem. A tame problem can be solved by a single solution and the problem ends when the solution is implemented (Rittel and Webber, 1973). This is because tame problems a limited set of rules and a beginning and an end. An example of a tame problem is a game of chess. There are rule regarding how the game starts, how the game ends and how each piece is allowed to move. While there are many ways the game can be played, the set goal is to defeat the other player.

Buchanan (1992) argues that design is a wicked problem, since there is no simple linear process to find the best design, nor are there any specific rules for designing a product. Instead, designs must be adapted to the specific situation and it is the job of the designer to identify and invent solutions to the problem based on its real world context. However, Coyne (2005) argues that wicked problems always have been part of the design process, and that designers are already addressing the wickedness with rules, goals and calculations.

In other words, even though wicked problems cannot be truly solved, there are ways to manage wicked problems. For example, Roberts (2000) proposed using network approaches to address wicked problems. In the paper, Roberts (2000) present three types of measures to manage wicked problems depending on how power is distributed, these are: authoritative, competitive and collaborative measures. The purpose of authoritative measures is to tame the problem, by focusing on the long-term benefits. The purpose of competitive measures, on the other hand, is to allow corporations the freedom to provide the market with a plethora of solutions, so that the market to decide which solution best fits. The purpose of collaborative approaches is to promote joint ventures and research projects so that the industry as a whole can move forward. According to Horn and Webber (2007), the way to manage wicked problems is to adapting to its cyclical nature, wicked problems do need to be re-learned, re-evaluated and re-solved as time goes on. They also emphasise that quick solutions are unlikely to lead to beneficial solution attempts, instead the use of substantial analyses are to be prioritised. On a similar note, Carroll et al. (2007) in their paper about managing forest fires, argues that working with incremental improvements, using knowledge and experience is the best way to address wicked problems.

4. Case studies

This chapter highlights, first, a brief overview of the case studies. This is then followed by a more in-depth description of each of the three case studies and the findings from them. In this chapter, both published and unpublished findings can be found.

4.1 Overview of the case studies

In order to find explanations of the phenomenon of renovation, three case studies have been undertaken. The first case study examined the renovation and vertical extension of six buildings, the main findings of which were results from a lifecycle profit analysis and lifecycle assessment. The aim of the second case study was to identify and explain the main challenges to the vertical extension of buildings. The purpose of the third case study was the development of six multi-active façade concepts. A summary of each study can be found in table 4.1.

4.2 Case study 1 – Renovation plus vertical extension

The aim of case study 1 was to assess the financial and environmental effects of energy-efficient renovation in a realised project. This aim requires an abductive approach where the researchers can pick and choose which aspects they find most relevant for reaching the aim. Since the object of study is a realised renovation project and the approach is abductive, a case study was chosen as the research method. The case study included interviews, site visits, documents and simulations. Given that the aim was to assess the financial and environmental effects of the renovation, lifecycle analyses were selected, since these provide assessments from the start of operation of the newly renovated building until the end of the expected lifespan of the renovated building. The case study was conducted by Åke Blomsterberg and Rikard Sundling. Papers 1 and 2 are based on the results from case study 1.

Table 4.1 Summary of the three case studies.

	Case study 1	**Case study 2**	**Case study 3**
Aim	Study the financial and environmental effects of energy-efficient renovation in a realised project	Study the development process regarding the implementation of vertical extension of buildings	Study and develop concepts of multi-active façades.
Research questions	1, 3 and 4	1 and 2	1 and 4
Research strategy	Abductive	Abductive	Abductive
Data gathering method	Document analysis, site visits and interviews.	Interviews, document analysis, and site visits.	Model assessment, industry data gathering and reference group discussions.
Type of data analysis	Economic and environmental lifecycle analyses	Development processes and success factors through the lens of the diffusion of innovation	Lifecycle profit analysis with a sensitivity analysis
Study conducted by	Åke Blomsterberg and Rikard Sundling	Rikard Sundling	Ricardo Bernardo, Stephen Burke, Åke Blomsterberg, Rikard Sundling, Petter Wallentén, Stefan Olander and Susanne Gosztonyi
Papers directly linked to the case studies	Papers 1, 2 and 4	Papers 2 and 4	Papers 3 and 4

This study was part of the Swedish contribution to the International Energy Agency (IEA) *Energy in Buildings and Communities Programme* (EBC) Annex 56 (Cost effective energy and carbon emissions optimisation in building renovation). It was funded by the Swedish energy agency [Energimyndigheten]. IEA EBC Annex 56 consisted of several studies, one of which was a multiple case study of best practice examples of energy-efficient renovation on which case study 1 was based.

Six similar four-storey buildings in the same neighbourhood, originally built in 1971, were studied. The buildings can be described as typical from the so-called *million homes programme*, with functional design and structures of prefabricated concrete. Before the renovation they were in bad shape since the buildings had not been well maintained and many features were still original: the energy use was 174 kWh/(m²·year). A picture of one of the buildings before renovation can be seen in figure 4.1.

Figure 4.1 One of the buildings from case study 1.1 before renovation.
Picture courtesy of Åke Blomsterberg.

In a pilot project, one of the buildings was renovated. The aim of the pilot project was to realise a renovation project to assess and learn from the experience. The pilot project renovation included several measures such as additional insulation to the building envelope, new windows, a heat recovery ventilation system and free-standing balconies. These improvements lowered energy use to 57 kWh/(m² year). Basically, everything except the concrete frame was replaced and improved. Figure 4.2 shows the pilot project after renovation. From a tenant's perspective, the renovation offered reduced draughts, reduced exposure to temperature fluctuations and an improved appearance.

Figure 4.2 The pilot project as one of the renovated buildings from case study 1.
Picture courtesy of Åke Blomsterberg.

The realised pilot project was in many ways a success; however, it was not considered a financial success. The housing developer hoped it would find opportunities to reduce the construction costs during construction, but it did not. This was a problem, since the five remaining buildings were in need of renovation. It was not until completion they realised that a vertical extension of the building could have made it financially viable. The combination of both renovation and vertical extension was thus used on the five remaining buildings. A picture of one of the buildings after renovation and vertical extension can be seen in figure 4.3.

Figure 4.3 One of the renovated and extended buildings from case study 1.
Picture courtesy of Åke Blomsterberg.

The aim of the study was to assess the financial and environmental effects of energy-efficient renovation using lifecycle analyses. The financial effects were analysed using a lifecycle profit analysis and the environmental performance were assessed using software called *Eco-Bat 4.0*, which simulates the performance of renovation over the whole expected lifespan. In order to perform the lifecycle cost analysis, the following inputs were required: construction cost, energy use, energy cost, maintenance cost, rent changes, discount rate and lifespan. The inputs were gathered from interviews, site visits and documents facilitated by the housing developer and the contractor. Construction cost, energy use and maintenance cost were simulated by the researchers and compared to the data from the documents in order to get the best possible results. The inputs needed for the lifecycle impact assessment were: the built-in materials for each renovation, the energy use and also information regarding the energy sources. The outputs of the lifecycle impact assessment showed the environmental performance with respect to the following factors: CO_2 emissions, cumulative energy demand, and non-renewable energy.

For more information about this study and the findings from it please see *other contributions* I, II and V. A summary of the financial evaluation from the study can be found in paper 3.

4.2.1 Findings from case study 1 – Renovation plus vertical extension

Summary of findings reported in paper 1

The aim of case study 1 was to assess the financial and environmental effects of energy-efficient renovation, using lifecycle methods for analysing the data. For this purpose, a case study of six similar four-storey buildings built in 1971 was carried out.

Four renovation concepts were studied: minimum (Min), code compliant (CC), low energy (LE), low energy plus vertical extension (LE+VE). The minimum concept is a reference case where a small number of improvements were made, mostly to the interior; it was assumed that none of these measures affected the energy use. The code compliant concept was supposed to embody the building code (BBR 2012) and the measures thus had to include improvements in both the building envelope and its technical systems. The reasons why the code compliant concept was created was that it would be interesting to see what it would take to go from the building standards in 1971 to what was considered newly built in 2012; additionally, it would also be interesting to compare standards for new buildings in 2012 to those for the realised pilot project. The low energy concept included significant improvements to both the building envelope and the technical systems. The low energy concept is a simulation of the realised pilot project. The low energy plus vertical extension concept was similar to the low energy concept but also included a vertical extension of two storeys.

Financial viability

The method chosen for examining the financial effects of the renovation concepts was a lifecycle profit analysis. The inputs for the analysis were gathered from documentation provided by the housing developer, interviews with both the project manager from housing developer and the site manager from the contractor, as well as site visits. The lifecycle profit analysis required six inputs: acquisition costs, rent changes, operation savings, current net operating income, lifespan and discount rate. The inputs for each of the four concepts from the analysis are presented in table 4.2. The results from the lifecycle analysis are also presented in table 4.2.

The results show that only the low energy plus vertical extension concept is financially viable. The results, thus, support the housing developer's decision to realise the low energy plus vertical extension for the five remaining buildings which were still in need of renovation. One of the reasons why the low energy plus vertical extension concept was viable was due to the added apartments which increase the rent of the building.

Environmental performance

The other part of the aim was to study the environmental performance of energy-efficient renovations, for this purpose, a lifecycle impact assessment used. The results from the lifecycle impact assessment are presented in table 4.3.

The result of the lifecycle impact assessment is that, overall, the low energy plus vertical extension concept is the one with the best environmental performance; however, as can be seen in table 4.3, it is only second best with respect to non-renewable energy. It should also be noted that the concepts are relatively close to each other. This is due to district heating, which is produced mostly from renewable energy sources. If more renewable renovation materials had been used then the environmental performance could have been further increased.

Another interesting result from the study was that only the tenants from four of the sixteen apartments moved back after pilot project. The main reasons for this were a significant rent increase of 30% and problems related to relocating the tenants during the construction work. Nonetheless, the tenants stated in a survey that they appreciated the improvements provided by the renovation such as better thermal comfort, indoor air quality and noise control.

Table 4.2 The results of the lifecycle profit analysis.

		Min	CC	LE	LE+VE
Acquisition cost [€/m^2]	Building envelope	59.5	168.5	218.1	198.3
	Plumbing	181.6	181.6	181.6	146.9
	Technical systems	4.0	87.6	95.5	95.5
	Fittings	363.1	363.1	363.1	293.8
	Total acquisition cost	**608.2**	**800.8**	**858.3**	**734.5**
Rent [€/m^{2}a]	Rent increase in existing apartments	8.7	14.1	17.3	17.3
	Rent from additional apartments	0.0	0.0	0.0	13.5
	Vacancy risk	1%	1%	1%	1%
	Σ Rent changes	**8.6**	**14.0**	**17.1**	**30.5**
Operation [€/m^{2}a]	Energy use [kWh/m^{2}a]	178	90	57	57
	Energy savings	0.0	7.3	10.0	6.8
	Maintenance savings	1.7	1.7	1.7	1.2
	Σ Operation savings	**1.7**	**9.0**	**11.7**	**8.0**
NOI [€/m^{2}a]	Rent changes	8.6	13.9	17.1	30.5
	Operation savings	1.7	9.0	11.7	8.0
	Current net operating income	13.5	13.5	13.5	9.2
	Σ Net operating income	**23.8**	**36.4**	**42.3**	**47.7**
	Lifecycle profit [€/m^2]	**-165.7**	**-122.1**	**-68.6**	**153.6**

As seen in table 4.2 and table 4.3, the results from the analyses show that the low-energy plus vertical extension concept could be considered financially viable and had arguably the best overall environmental performance of the concepts. Since these buildings are typical of *the million homes programme*, perhaps similar renovations can be realised elsewhere; however, it should be noted that the required rate of return was 3.8%, which is low.

Table 4.3 The results of the lifecycle impact assessment.

		Min	CC	LE	LE+VE
Global Warming Potential [kg eq. $CO_2/a/m^2$]	Materials – building envelope	1.2	1.3	3.4	2.5
	Materials – technical systems	0	0.4	0.4	0.4
	Heating	11.6	4.8	2.1	2.1
	Hot water	2.7	2.1	2.1	2.1
	Power and lighting	0.8	0.8	0.7	0.7
	Total	**16.3**	**9.4**	**8.7**	**7.8**
Cumulative Energy Demand [MJ/m^2a]	Materials – building envelope	19.4	18.9	48.4	35.2
	Materials – technical systems	0	6.9	6.9	6.9
	Heating	156.8	64.8	28.4	28.4
	Hot water	36.4	28.4	28.4	28.4
	Power and lighting	89.8	89.8	78.6	78.6
	Total	**302.4**	**208.8**	**190.7**	**177.5**
Non-Renewable Energy [MJ/m^2a]	Materials – building envelope	17.4	18.4	47.2	34.3
	Materials – technical systems	0	6.5	6.5	6.5
	Heating	31.4	13.0	5.7	5.7
	Hot water	7.3	5.7	5.7	5.7
	Power and lighting	66.4	66.4	58.1	58.1
	Total	**122.5**	**110.0**	**123.2**	**110.3**

4.2.2 Other findings not reported in attached publications

Another interesting result from the study was that the heating source was by far the most impacting factor with respect to the environmental performance. Figures 4.4 and 4.5 show this effect. If the goal is to minimise carbon emissions then concepts using electricity or district heating ought to be prioritised; these energy sources are significantly better than *any* renovation concept using fossil fuels, i.e. oil or gas, (see figure 4.4). However, the same cannot be said for primary energy. While district heating remains the best option, electricity is the worst option (see figure 4.5). This is probably due to the many steps and, thus, losses in the production and delivery of electricity. The results from this study suggest that, if possible, one should use district heating as it proved to be the most appropriate heating source. For more information about this result please read the IEA Annex 56 publications and deliverables.

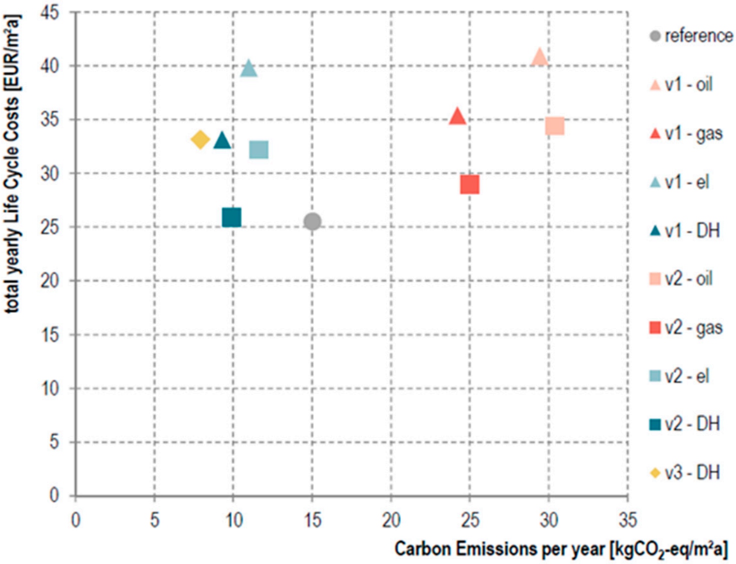


Figure 4.4 A graph of carbon emissions per year as a function of total yearly lifecycle costs.

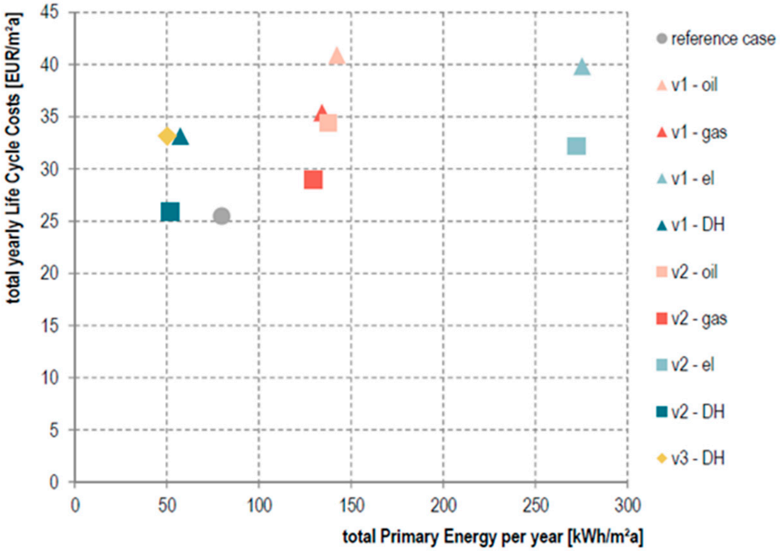


Figure 4.5 A graph of total primary energy per year as a function of total yearly lifecycle costs.

4.3 Case study 2 – Finding a development process for extending buildings vertically

The aim of case study 2 was to examine the development process concerning the vertical extension of buildings. In line with case study 1, this aim requires an abductive approach where the researchers can pick and choose those aspects which they find most relevant. A case study is also fitting here, since the aim requires a phenomenon in its real-world context. Moreover, research targeting this aim would greatly benefit from studying multiple buildings which have been vertical extended. The data gathering methods used was interviews, site visits and document analysis. The goal of the data gathering was to identify success factors in the decision-making process from the four projects and, from there, outline a development process that tied all these factors together. Paper 2 is based on the results of case study 2.

Case 1 consists of four multifamily buildings, built in the late 1970s, with structural frameworks of concrete and façades of brickwork. The planned extension would consist of two storeys and would be considered as a separate buildings (see figure 4.6); this would mean that the existing buildings would not undergo any renovation or refurbishment.

Figure 4.6 The proposed vertical extension for one of the buildings from case 1.
Artwork curtesy of Tengbom Arkitekter and MKB.

Case 2 consists of five multifamily buildings from 1971, with structural frames and façades of concrete. The planned extension consisted of two storeys and was combined with a renovation of the entire building (see figure 4.7). As mentioned in case study 1, the original plan was not to extend, but simply to renovate;

however, as the pilot project showed, the renovations would not have been financially viable without the vertical extensions.

Figure 4.7 The realised renovation plus vertical extension of one of the buildings from case 2. Photograph courtesy of Åke Blomsterberg.

Case 3 consists of 18 multifamily buildings, built in 1969, with structural frames and façades of concrete. The buildings were extended by two storeys, even though the original plan was to renovate the existing buildings (see figure 4.8). It should be mentioned that the extensions for the first few buildings were based on structural timber frames; these were later changed to steel frames due to the contractor changing its policy.

Figure 4.8 The realised renovation plus vertical extension of one of the buildings from case 3.

Case 4 consists of four multifamily buildings, built in the late 1950s, three storeys high and with brick façades. The planned single-storey extensions would have been considered separate buildings and, thus, the existing buildings were not intended to undergo any renovation (see figure 4.9). The extension project was cancelled shortly after the housing developer received bids from contractors as they were much higher than expected.

Figure 4.9 The proposed vertical extension for one of the buildings from case 4.
Artwork curtesy of Jaenecke Arkitekter.

4.3.1 Findings from case study 2

Summary of findings reported in paper 2

This study examined the development process and the success factors for extending buildings vertically. In addition, efforts were made to link the results from the study to the diffusion of innovation, since vertical extensions are an innovation still in its early phases. In this study, four cases of vertically extended buildings were investigated, two of which were realised, one of which was cancelled and one that was in the planning phase. The results from the study were summarised into success factors, which were then further summarised into seven development steps. These steps were structured into a development process and each step was further explained with the aid of literature. The seven-step development process can be seen in figure 4.10. In summary, the development process is a step-by-step flowchart of the most important factors that have to be considered when planning for the vertical extension of a building. A lot of information could have been included in the steps; however, information which is not related to the vertical extension of buildings is not elaborated in this study.

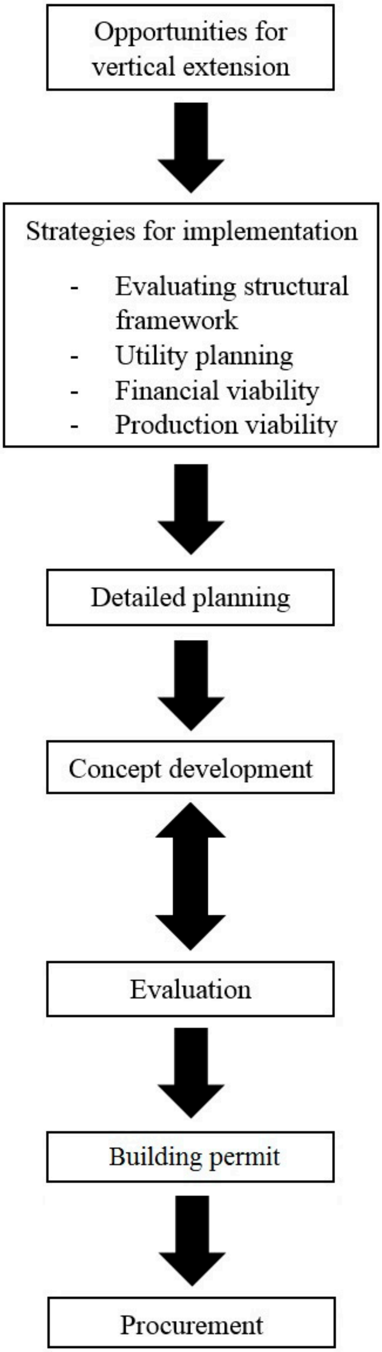


Figure 4.10 The development process.

Opportunities for vertical extension

The people who were interviewed generally agreed than an extension is typically more expensive than newly built apartments; thus, finding the right location and building for an extension is key. All four buildings, which were studied were located in dense urban environments (at least from a Swedish perspective), with high demand for housing. The buildings were all also smaller than the surrounding buildings in the neighbourhood; in other words, an extension would not significantly change the character of the urban context. Another important opportunity is to search for large extensions, since maximising the amount of living space in the extension should be the target. In this way, the unit cost of building the extension (i.e. per m^2) is reduced.

Strategies for implementation

Evaluating structural frameworks

According to the National Board of Housing, Building and Planning (Boverket) about 775 000 apartments were built between 1961 and 1975 (Boverket, 2010); among these roughly 60% are in need of renovation. Multifamily buildings from this era usually have an oversized structural frame of concrete or loadbearing brickwork, which could be suitable for vertical extensions (Bergenudd, 1981). This means that there is a lot of potential for the vertical extension of buildings in Sweden. As noted earlier, all cases in the study were of buildings from that period. Even though oversized structural frameworks were the norm, the loadbearing capacity of the structural frame has to be determined individually.

Reinforcement can support a structural frame be it in the foundations, as seen in cases 1 and 2, or as an external framework, as seen in case 4. However, reinforcement can allow improvements other than structural strength. In cases 2 and 3, reinforcement allowed for a different apartment layout in the extensions, this meant that the building could now appeal to a wider range of tenants. Reinforcement can also allow for additional installation room for building services.

Planning building services installations

In some of the reported cases, the existing shafts were large enough to house the new installations; in other cases, new shafts had to be made. It should be noted that installations are typically not designed with a future extension in mind; therefore, it is likely that new installations have to be designed. An interesting result from Case 3 was that reinforcement between the extension and the existing building was used to rearrangement the building installations for the extension. According to current planning and building legislation, any building with more than one storey is recommended to have an elevator; however, every building of more than three storeys is required to have an elevator. Therefore, any extension resulting in a building with three or more storeys either has to extend the existing elevator shaft or has to install a new elevator.

Financial viability

A preliminary financial viability test of the project is suggested. This test should be a simple prognosis which takes into consideration the output from the previous steps. If there are no financially viable options, it is better to stop the project sooner rather than later; otherwise, one might spend unnecessary time and money on planning such as in case 4.

The reason for selling the apartments in the buildings from case 3 after the extensions was never revealed; however, it could have been that the renovations plus extensions were more expensive than planned and that selling the apartments was a way of financing the projects. Another possibility is that the housing developer wanted to sell in order to purchase other buildings or to finance other projects.

Another strategy which was successful in cases 2 and 3 is that a vertical extension could finance the renovation of the older apartments. Cases 1 and 4 did not attract any financially viable bids in the procurement process; in these cases, the extensions would have been considered separate from the existing buildings. This suggests that there might be strong synergistic financial effects between renovation and vertical extension which have yet to be fully understood; however, some information in support of this argument can be found in case study 1.

The planners of vertical extension projects have to understand that these projects are both expensive and complicated. According to the project manager in case 4, their preliminary evaluation of the project seemed to confirm financial viability; however, when the bids were received they realised that they had been too optimistic. It can be argued that the problems with case 4 were that the amount of living space in the extension was simply too little. There were a lot of relatively fixed costs, such as elevators, building services installations, reinforcement and roof construction, which do not scale linearly with the size of the extensions. Thus, a significant amount of living space has to be added.

Production viability

As understood from case 1, many contractors see high-density urban environments as a barrier. Limitations on space and transportation, disturbing local residents and falling materials are risks which have to be managed. Therefore, housing developers have to be aware of these risks and have preliminary ideas on how to manage them. Otherwise, the bids that they receive during the procurement process will reflect the uncertainties that these risks represent.

Detailed planning process

A success factor from cases 1 and 4 was the collaboration between the housing developer and the municipality. This collaboration meant that the process of changing to the detailed plans and applying for the building permit was simplified, since it essentially was part of the design process. However, since a vertical extension will increase the size of the building and thus the amount of shading, one complaint that housing developers should expect is that of reduced natural light in the neighbouring buildings.

Concept development

During concept development, one should search for and combine synergistic effects, using what was learned from earlier steps. Above all, it is necessary to identify the main goals of the extension project and work from there; additionally, risks also have to be managed. The concept needs to be well though through and holistic before concepts are evaluated. It is advisable to develop several concepts so that the results of the evaluation can be compared.

Evaluation

The property developer has to decide which parameters are worth evaluating; typically, this includes financial, social and environmental performance. Additionally, an assessment of the project risks is key to success. A feedback loop between the concept development step and the evaluation step is needed in order to optimise each concept and to filter down to one preferred concept.

The lack of proper evaluation might lead to difficulties or the end of the project, such as in cases 1 and 4. In these cases, the developer had no plan for managing the risks during construction before starting the procurement phase. This resulted in case 1 having to be taken back to the concept development step: case 4 was simply cancelled.

In case 2, the housing developer evaluated several different renovation options in a lifecycle cost analysis of the pilot project. In other words, it knew that the renovation of the pilot project would be financially unviable before realisation. The purpose of the analyses is to provide depth and understanding to the options in the decision-making process: the outputs are not meant to be seen as facts. Even though the outputs of the analyses might not support decision-making, in some cases one has to understand that reality is different from prognosis. Therefore, the housing developer decided to go through with the pilot project anyway in the hope of finding solutions to the financial problem.

Building permit

No data suggested that the building permit process for a vertical extension was significantly different from any other building permit process, so this step was not further elaborated.

Procurement

Construction in a dense urban environment, where most vertical extension of buildings projects take place, does bring several challenges. The identified challenges include little space for the construction site, high traffic loads, working on a high level, falling materials and disturbing local residents. Thus, before sending the chosen concept to contractors as part of the biding process, the developer has to identify those risks that the projects could face during construction. Not doing so might lead to no bids being received, such as in case 1.

4.4 Case study 3 – Financial evaluation of multi-active façade concepts

This case study was part of a research project named "Pre-study of prefabricated multi-active façade elements for energy renovation of multi-dwelling buildings" and was sponsored by the Swedish energy agency's [Energimyndigheten] research programme E2B2 and the Swedish construction industry's organisation for research and development [SBUF]. Just as the name suggests, the aim of the project was to assess whether or not multi-active façades could be viable for renovations in a Swedish context. Other studies have been undertaken on multi-active façades, but these have mostly been in central European countries; for examples, see MORE-CONNECT (2018). Thus, there was a need for a study on how multi-active façades could be used in Sweden. The research project consisted of several work packages: the first studied the renovation needs and relevant laws and requirements in Sweden; the second studied passive renovation technologies such as insulation and windows; the third studied active technologies such as ventilation and photovoltaic systems; and, the fourth studied financial aspects. Two buildings were assessed in this case study, figure 4.11 show the low-rise building and figure 4.12 show the high-rise building. The main focus in this dissertation is the fourth work package. The financial aspects were mostly centred on a lifecycle profit analysis, in which the following parameters were analysed: construction costs, maintenance costs, energy costs and price changes. Additionally, discussions on existing insulation materials, centralised versus decentralised systems, prefabrication versus on-site construction and acoustics were conducted in order to narrow down the possible renovation concepts before doing more detailed lifecycle analysis. The lifecycle profit analysis was similar to the one in case study 1, the main difference being that price changes were included so that a sensitivity analysis could be performed. This sensitivity analysis provided the study with a much-needed debate on the effects of small price changes over the course of long lifespans. Paper 3 is a summary of the results from case study 3.

Figure 4.11 The low-rise building.
Picture curtesy of Ahmed Hadzimuratovic and Marcus Swedmark.

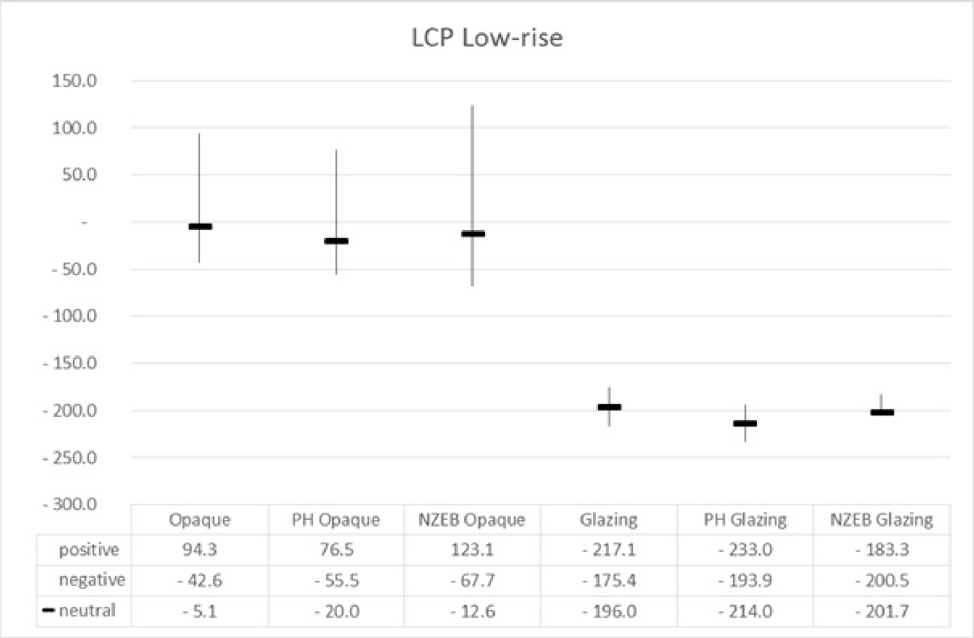
Figure 4.12 The high-rise building.
Picture curtesy of Ahmed Hadzimuratovic and Marcus Swedmark.

4.4.1 Findings from case study 3

Summary of findings reported in paper 3

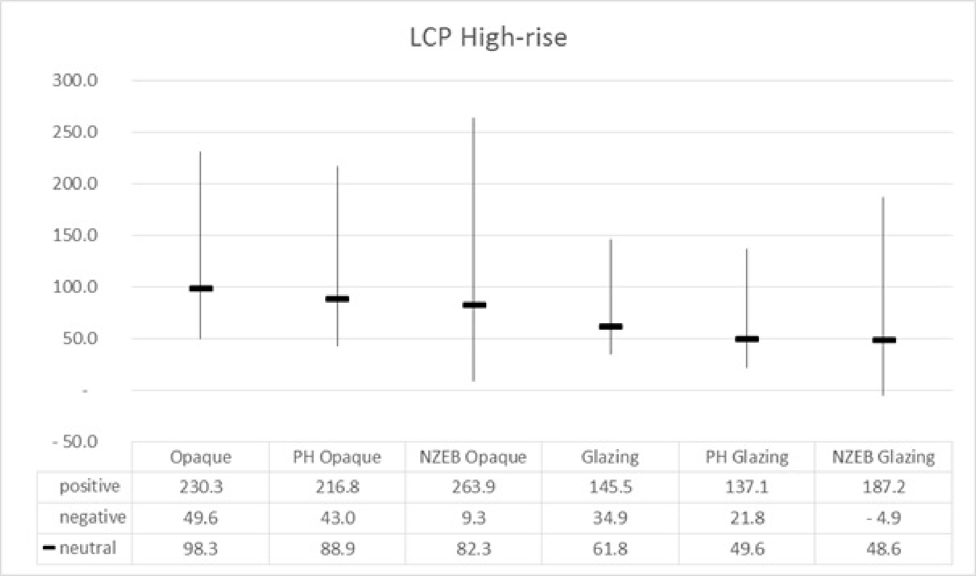
It was decided in the early phases of the research project that a multi-active façade would be defined as a prefabricated façade with integrated systems. The integrated systems which were investigated were ventilation, photovoltaic, insulation and glazing. A lifecycle profit analysis adopted from Davis Langdon (2007) was used in this study to assess the financial viability of six renovation concepts. Figure 4.13 and figure 4.14 show the results of the analysis. A short discussion of the results can be found below, but for more information about the method, the inputs and the results from this analysis see paper 3.

The results are contradictory, the analysis shows that none of the multi-active façade concepts are financially viable when applied to the low-rise building (see figure 4.13); but when applied to the high-rise building all concepts are viable (see figure 4.14). There are two reasons which might explain this apparent contradiction. First, the low-rise building is slim and long, in other words there is a large area of façade in relation to living space. Second, the existing brick façade on the low-rise building is a barrier, as it is expensive to demolish and remove.



	Opaque	PH Opaque	NZEB Opaque	Glazing	PH Glazing	NZEB Glazing
positive	94.3	76.5	123.1	- 217.1	- 233.0	- 183.3
negative	- 42.6	- 55.5	- 67.7	- 175.4	- 193.9	- 200.5
▬ neutral	- 5.1	- 20.0	- 12.6	- 196.0	- 214.0	- 201.7

Figure 4.13 The results from lifecycle profit analysis for the low-rise building.



	Opaque	PH Opaque	NZEB Opaque	Glazing	PH Glazing	NZEB Glazing
positive	230.3	216.8	263.9	145.5	137.1	187.2
negative	49.6	43.0	9.3	34.9	21.8	- 4.9
▬ neutral	98.3	88.9	82.3	61.8	49.6	48.6

Figure 4.14 The results from lifecycle profit analysis for the high-rise building.

The glazed concepts suffer from a 25-year expected lifespan of the façade glazing, which leads to significantly higher maintenance costs compared with the nonglazed concepts. In the low-rise buildings, the balconies are extended which further lowers their financial viability; however, if the expected lifespan of the glazing could be extended to 30 years and the extended and glazed balconies could lead to a rent increase of €250 per apartment, one of the glazed concepts would become the preferred alternative.

4.4.2 Other findings not reported in attached publications

The name multi-active façades might seem a little deceptive since in our study we chose only to include insulation, ventilation ducts and photovoltaic panels in the façade. However, it should be noted that a primary evaluation of several other systems was undertaken as well; namely, nonconventional insulation materials, decentralised heating systems and innovative heating systems. Innovative heating systems are not elaborated here: for more information see Gosztonyi et al. (2017).

Nonconventional insulation materials

In the building envelope, traditional methods are to a large extent still used (Skanska 2010), which leads to thick insulated walls and thus less functional space within the building. There is a need for better and higher performing insulation materials. Berge (2013) shows the thermal conductivities of several insulation types, compared to the thermal conductivity of air. Cellulose, mineral wool and expanded polystyrene/extruded polystyrene have a higher thermal conductivity than polyurethane, aerogels and vacuum insulation panels, and are thus less efficient. Skanska (2010) undertook a comparative study to investigate different high performing insulation materials, namely vacuum insulation panel, aerogels, expanded polystyrene with graphite, polyurethane and polyisocyanurate.

In summary, these materials have yet to make a significant impact on the market and still need development. Other materials such as phase-shifting materials need even more development before they can be used commercially. Berge (2013) analysed the application of aerogels and vacuum insulation panels and concluded that the increased cost from using the new materials could be balanced against the additional benefits this would bring; for example, reduced wall thickness and change aesthetics. However, the results from our study does indicate that since the concepts using traditional insulation were barely financially viable, further increasing the construction costs would be unlikely to result in viable concepts. Nevertheless, in specific projects where wall thickness would be a limiting factor, higher performing insulation materials could be useful.

Centralised versus decentralised systems

Centralised systems are better from an efficiency perspective. Centralised systems may be the better option since some of the individual parts of heat pumps have a certain minimum size, thus making a decentralised system harder to optimise and more expensive. There are usually benefits with having one large centralised system such as increased efficiency and less internal losses. One of the reference group members noted that, in one of their earlier research projects, they implemented and studied the effects of decentralised systems; however, they found that decentralised systems are suboptimal in terms of efficiency compared to centralised systems.

Additionally, decentralised system may require more maintenance. The more technical systems installed the higher is the likelihood of failures. Moreover, a decentralised system needs to be easy-to-access, otherwise maintenance will be difficult. On the other hand, if a centralised system fails it will affect every resident, whereas a failure in a decentralised system will only affect one apartment.

Decentralised systems might introduce faults in the façades. Another reference group member noted that, as a manufacturer of prefabricated façade elements, they want to remove as many uncertainties as possible so that they can assure their clients that their façade elements are a long-term investment without problems. This is the main reason why this particular company has chosen to use inorganic materials only such as steel and foam. These materials have a long individual lifespan, are chemically resistant and are not sensitive to moisture. Introducing technical systems in the façade elements introduces the risk of moisture problems or reduces the elements' capacity to insulate. Technical systems might also affect the lifespan of the façade as a whole negatively, since the technical system typically has a lower expected lifespan than, for example, insulation and structural frameworks.

Prefabrication versus on-site construction

Throughout the project, there had been discussions regarding prefabrication versus on-site construction. Fortunately, participants in our reference group now actively work with both methods. On-site construction is more adaptable and problems in design and tolerance issues can usually be solved on site. Prefabricated elements have to rely on accurate designs and precise construction; however, prefabricated elements do have some flexibility, thus allowing for smaller tolerance issues. Prefabrication also offers better control over the work environment. The skilled workers have access to more specialised tools which require a factory; for example, flip top workbenches, specialised hand tools and cross-line laser support. A benefit for the workers is that a more controlled work environment can lead to fewer accidents and incidents. Some of the most common accidents in the construction industry are falls and loss of control (Samuelson, 2014). Since the workspace is stationary and the work more monotonous, several risks can be eliminated such as falls from heights and heavy lifting. Moreover, risks such as loss of control of machines, tools, transport and material can be significantly reduced, with the same true of accidents due to a messy or dirty workplace.

Relocating the residents is expensive and, more importantly, it generates a lot of concerns. Expenses include missed rent and relocation of the residents with all of their belongings to the new apartment and back to the renovated apartment. However, the biggest expense of relocation can be the loss of residents. Many residents simply move somewhere else rather than suffer the consequences of relocation. In the pilot project from case study 1, relocation lasted a year and caused 12 out of 16 residents not to move back into their renovated apartments. The majority of the residents were offered apartments with similar standards to what they previously had by the housing company and in the same neighbourhood. Therefore, it would be beneficial for the both the housing company and the residents if relocation could be avoided. According to a proponent of prefabrication in the reference group, one of its benefits is renovation without resident relocation. In some cases, a relocation is unavoidable; for example, if the renovation includes a lot of indoor refurbishment. Nevertheless, if only the façade is in need of renovation then a relocation might be avoided. However, the same can be true for on-site construction; but, with prefabricated façade elements, a much faster renovation is possible which reduces the turmoil and inconvenience for residents. In case study 3, it was decided that the tenants would not be relocated but would be compensated by not paying rent during construction.

Parameter analysis from case study 3

In an attempt to better understand the lifecycle profit analysis tool and how it can be applied to energy-efficient renovation, a parameter study was performed. The aim was to highlight the most important parameters regarding the financial viability of energy-efficient renovation of multi-family buildings, as well as show how much the results can be affected by small changes over a long period.

The opaque concept applied on the low-rise building from case study 3 was chosen, mainly because the results from the lifecycle profit analysis showed that it was close to zero, i.e. that it was right on the line between what is considered financially viable and what is not. The parameter analysis was made concerning the following: construction costs, lifespan, discount rate, heating price, heating price change, electricity price, electricity price change, maintenance price and maintenance price change. The parameters, their estimated values and the variability for each of the estimated values can be seen in table 4.4.

Table 4.4. The parameters analysed with their estimated values and the variability of the estimated values.

	Estimated value	**Variability**
Construction costs	118.3 €/m^2	±10%
Lifespan	40 years	±10 years
Discount rate	5%	±25%
Heating price	3.79 €/m^2	±20%
Heating price change	1.7%	±50%
Electricity price	0.25 €/m^2	±20%
Electricity price change	1.4%	±50%
Maintenance price	5.55 €/m^2	±20%
Maintenance price change	1.9%	±50%

The construction costs, heating price, heating price change, electricity price, electricity price change, maintenance price and maintenance price change were all identified in case study 3 (see paper 3 for more details). The lifespan and discount rate were estimated using the findings from Farsäter et al. (2015). The variabilities are based on relatively likely prognoses. For example, some companies assume a 30-year lifespan and others assume 50-year lifespans and have their arguments for their choice; but it seems most companies could accept a lifespan somewhere between 30 to 50 years. Additionally, the electricity price depends on where the building is located, because in some regions it is cheaper and in others it is more expensive. It was accepted that a 20% price difference was realistic. Another is the heating price change, some argued that it will increase in the future due to climate change; however, another scenario is that renewable energy systems are subsidised and might thus lower heating costs.

A significantly ignored parameter is that of residual value; here, one could argue that the residual value is zero at the end of the lifespan. However, when the lifespan changes from 50 to 30 years there is a difference of 20 years. This means that there is possible 20 years of use left; thus, there is a residual value. Nevertheless, one can never be too sure about the technical lifespan as there might be disruptive technologies which could make renovation measures obsolete.

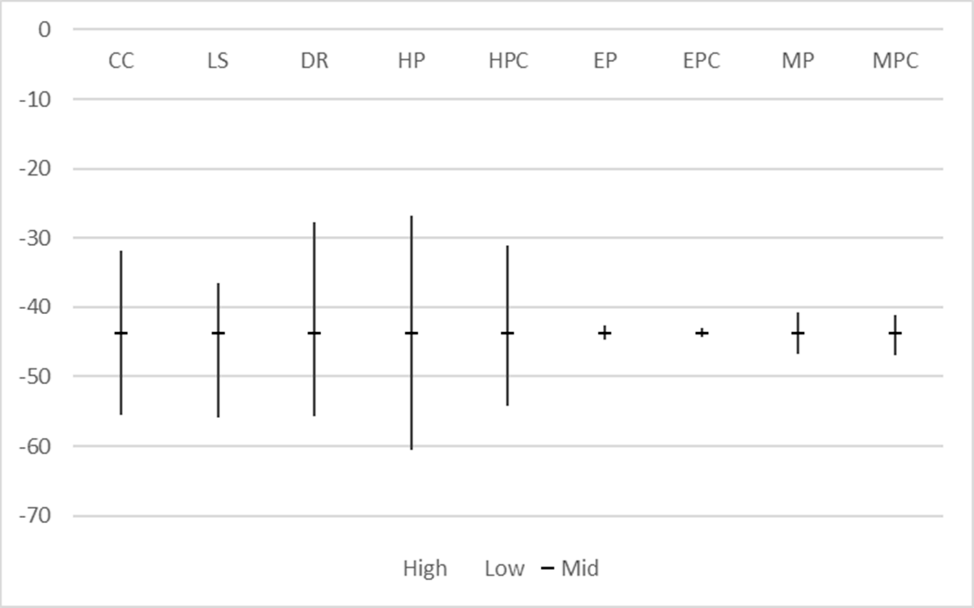


Figure 4.15 The results from the parameter analysis.

The results presented in figure 4.15 show that there are five parameters which have a significant impact on the results: construction costs, lifespan, discount rate, heating price and heating price change. Electricity price, electricity price change, maintenance price and maintenance price change are on the other hand almost negligible when compared.

One could build on this further as part of future research and undertake a Monte Carlo simulation of the varying parameters.

4.5 Further findings from the case studies

As highlighted in Chapter 1.1 *Background* there is an accumulated need to renovate buildings since the building stock is getting older. Additionally, energy-efficient renovation can contribute significantly to the European and National greenhouse gas emission targets. As has been show in case study 1 and case study 3, energy-efficient renovation can reduce the energy use and can be argued to be financially viable, given appropriate circumstances. Moreover, case study 1 and case study 2 present vertical extension of buildings as a way to densify cities and as a possible enabler for energy-efficient renovation. However, neither energy-efficient renovation nor vertical extension has seen large-scale implementation.

4.5.1 Summary of findings reported in paper 4

In paper 4, it is argued that this lack of renovation is because the renovation of buildings is a wicked problem. As mentioned in Chapter 3.5 *Wicked problems* a wicked problem is a problem which is impossible to solve since the problem develops as new solutions are attempted (Rittel and Webber, 1973). The argument that renovation is a wicked problem is based on a discussion of several aspects of renovation, these are: technical, financial, environmental, urban development, stakeholder participation, tenant behaviour and current policies.

A technical issue which might occur is moisture related damage. However, it cannot be considered wicked since problems such as moisture are solvable. As highlighted in case studies 1 and 3, finding financially viable renovation concepts is challenging; it might be easier to find other more interesting investment alternatives. The wickedness of the financial analysis largely depends on the large impact small changes have given the long lifespans involved and how the financial outcome affect the stakeholders. A similar argument can be made regarding environmental performance. However, the many different factors which are linked to environmental performance introduce further wickedness. This is because, no one factor can be claimed to be the most important one, nor can one factor be translated into another one. Gentrification is a problem which can be linked to the renovation of buildings. As presented in case study 1, 12 out of the 16 tenants chose not to move back after the construction work was complete. A proposed method to limit the problems of gentrification is stakeholder involvement. However, as highlighted in Conference paper III (Martínez Àvila et al., 2016), one developer saw stakeholder involvement more as a way to legitimise their projects. Another confusing aspect of renovation is current policies in Sweden; in short, the current policies both incentivise and limit renovation. This is causes confusion amongst the practitioners, since how the policies are interpreted will vary depending on which stakeholder is doing the interpretation.

All in all, these points show that the renovation of buildings is a wicked problem, and when compared to the characteristics of wicked problems, renovation fits all of them.

5. Discussion

In this chapter, the answers to the research questions are discussed. The purpose is to provide explanations by combining the knowledge from the reviewed literature and the findings from the case studies.

5.1 How does complexity impact the success of renovation projects?

Renovations are complex endeavours and, as reported in the further findings from the case studies, it can be argued that it is a wicked problem, since there are several aspects of the renovation of buildings which have wicked characteristics. For example, the renovation of buildings is linked to gentrification, as shown in findings from case study 1, 12 out of the 16 tenants chose to not move back to the renovated building, mostly because of increased rent. Harvey (2008) supports this argument and argues that the right to the city resides with the political and economic elite. Additionally, as shown in findings from case study 3, the financial viability of renovation projects largely depend on which input is used in the analysis and how it changes over time. On the other hand, Feenberg (2017) argues that empirical data can be used to serve the interests of dominant actors; for example, by arguing for increased rent because of the lacking financial viability of renovations. Moreover, Huets and Mol (2013) identified that what makes a great product largely depend on who you ask.

By its definition, wicked problems cannot be solved (Rittel and Webber, 1973); However, Head (2018) points out, while solving wicked problems is fundamentally flawed, trying to cope with and manage wicked problems is possible. For example, Horn and Webber (2007) suggest that by understanding and adopting to the cyclical nature of wicked problems solutions can continuously be implemented. Even though no single solution will please all stakeholders, this approach will mean that each new solution can address the current needs of the stakeholders, see Conference paper III (Martínez Àvila et al., 2016). The problem is that this approach is not applicable to the renovation of buildings, because of the planned long lifespan of the renovated building. One could naturally plan for incremental improvements or plan to renovate the building more often; however, that would negatively affect the financial viability, which is already questionable, as will be discussed later.

It should therefore come as no surprise that many developers are reluctant to renovate their building stock. As highlighted in case study 2, misunderstanding or not addressing the complexity of renovations might lead to project cancelation.

5.2 To what extent is it possible to define a development process for renovation projects?

As recently discussed, the renovation of buildings is a complex process, and while it is not possible to find a perfect solution, there is still a need to renovate buildings. The purpose of defining and studying the development process, is therefore to share knowledge and experience about the process.

Addressing wicked problems by adopting to its cyclical nature does not work particularly well regarding the renovation of buildings; however, Horn and Webber's (2007) argument, that it is possible to manage wicked problems by re-learning, re-evaluating and re-solving them, might contribute. While it is not feasible to use this approach for one building, it is possible to learn for other renovation projects. By re-learning, re-evaluating and re-solving already renovated buildings, one can gain knowledge and understanding before attempting to renovate.

Case study 2 highlights the success factors and lessons learnt from four different vertical extension projects, but it also builds on two other studies on the topic of vertical extension, namely Bergenudd (1981) and Lidgren and Widerberg (2010). The development process which is presented consists of seven steps, and is meant to be help during the planning phase. While the presented development process is focused on the vertical extension of buildings, one could probably identify a similar process for energy-efficient renovation of buildings and perhaps renovation in general.

However, due to the project-based nature of the construction industry, there are many unique buildings which will require tailor-made renovation concepts which can influenced diffusion of innovation negatively (Lindgren and Emmitt, 2017). Therefore, it should not be assumed that the presented development process will work for every vertical extension project. While the process might be similar, each project is unique and might therefore benefit from an alternative process.

5.3 To what extent is improved environmental performance possible through renovation?

The results of case study 1, show that concerning global warming potential, energy-efficient renovations have the possibility to reduce CO_2 emission by about 50%. As highlighted by Crawford (2011) the purpose of lifecycle impact assessment is in part to compare environmental performance between different alternatives. Therefore, from a global warming potential perspective, the low-energy plus vertical extension is the preferred alternative; the same can be said from an energy use and cumulative energy demand perspective. However, from a non-renewable energy perspective, the study found no noteworthy benefit. Instead, from the perspective of non-renewable energy, the energy-savings are not enough to motivate the renovation. Crawford (2011) also offers insight here, a second purpose of lifecycle impact assessment is to identify areas for improvement. A proposed improvement, highlighted in Conference paper I (Blomsterberg and Nilsson, 2016), could be to install cellulose insulation which would lower the non-renewable energy by about 10%. However, in their paper on energy-efficient renovation of multi-family buildings in Sweden, Gustafsson et al. (2016) did show a non-renewable energy reduction by 56%.

As shown in case study 1, the heating source is the most important aspect to consider when trying to maximise environmental performance. Of the four heating sources analysed, district heating was deemed the best. It should also be noted, just as with the financial analysis, that a prognosis does not guarantee real outcome, which is supported by Ayres (1995) and Ott et al. (2014). For example, as it stands today district heating is probably the preferred alternative; however, if the policies surrounding the burning of waste, the preferred alternative might be another heating source, like electricity.

Moreover, the two other performance factors, cumulative energy demand and non-renewable energy, are also worth minimising, one needs to think carefully regarding how which factor to prioritise; or, one could for example use a multi-criteria decision making approach to make a more balanced decision, but this has been out of scope for this research.

5.4 To what extent can the financial viability of renovation projects be evaluated?

As argued in Chapter 3.4 *Lifecycle profit analysis*, in order to evaluate financial performance one must consider all financial aspects. Simple methods, such as payback period, fail to grasp the long-term effects of renovation measures, such as discount rate and price changes. The lifecycle cost and lifecycle profit analyses can take these aspects into account; however, by its definition, the lifecycle cost analysis does only consider costs and not income.

The financial effects are the focus of case studies 1 and 3. In both case studies, it is shown that it is possible to identify financially viable renovation concepts; however, doing so can be quite challenging. It should be noted, that in both case studies, the assessment were made from the perspective of municipal developers; who typically have low required rates of return compared to then private companies. If a higher discount rate would be used in the analyses, less concepts, if any, would be financially viable.

Additionally, as highlighted in Chapter 2.7 *Validation discussion* it is possible that the calculations were flawed in some way. There are several inputs required to do a lifecycle profit analysis. In the case studies presented here, all inputs are more or less qualitatively determined, so there is a significant margin of error. Although, Gluch and Baumann (2004) explain that this is a fundamental flaw of the method. Both Gluch and Baumann (2004) and Crosbie et al. (2011) highlight the importance of identifying reliable input data, without it, the practical usefulness of the lifecycle profit method is questionable.

Moreover, most of these inputs are also of significant importance to the result of the analysis. As show in the findings of case study 3, just small cost differences or price changes can have significant impact on the outcome of the analysis; thus, it is unlikely that the results of the analysis is what actually will realise in the future. This is in line with the suggestion by Ludvig (2013), that lifecycle analyses are best seen as tools meant to increase the understanding of the lifecycle of the building.

It is therefore suggested to do a sensitivity analysis to see the spread of possible outcomes; however, it should also be noted that a sensitivity analysis does neither guarantee a realistic prognosis, since a sensitivity analysis is also based on predictions which might be wrong. Nevertheless, a deep diagnosis of the building which is then used in a well thought out prognosis, even if it is fundamentally flawed, is still the preferred tool for increasing understanding before making a decision.

6. Conclusion

In this chapter, the final conclusions of the research are presented. Additionally, contributions to both academia and practitioners, as well as, suggested further research are also presented.

6.1 Final conclusions

As reported in Chapter 4.5 *Further findings from the case studies*, there are several challenges regarding the renovation of buildings which essentially makes it a wicked problem. As shown in findings from case studies 1 and 3, there are opportunities for finding financial viability renovation concepts; however, long-term prognoses are sensitive, even to small changes, this means that the results are unlikely to realise in practice. Additionally, as shown in case study 1, whether or not the renovation is beneficial from an environmental performance perspective, largely depends on which environmental factors are assessed. Moreover, as highlighted in Chapter 3.2 *Vertical extension of buildings*, renovation can be linked to gentrification; for example, in case study 1, twelve out of the sixteen tenants did not move back after renovation. In theory, one could perhaps minimise the negative consequences and maximise the benefits to find one optimal renovation concept, but in practise, it is impossible to find an optimal renovation concept. Even so, as presented in Chapter 3.5 *Wicked problems*, by adapting to the cyclical nature of wicked problem one could potentially manage them. However, these approaches are not easily applied to the renovation of buildings, due to the long lifespans involved.

Because renovations are complex processes, it is essential to share knowledge and experience. By highlighting the most important success factors in a described development process, as the done in case study 2, one could aid the diffusion of innovation and the implementation of more renovation projects. However, it should not be assumed that such a development process can be used in every project, instead it serves better as a recommendation or as a source for inspiration.

The findings from case study 1, show that renovations can reduce energy use by 68%, global warming potential by 52%, cumulative energy demand by 41% and non-renewable energy by 10%. This means that significant improvements to environmental performance can be achieved. Even so, it will depend on which factors are chosen for assessment. Since only three environmental factors were assessed in this research, no conclusions can be made regarding the impact of renovation on other factors. Moreover, case study 1 also highlight, that the heating source is the most important aspect to consider when trying to improve environmental performance, at least in terms of global warming, cumulative energy demand and non-renewable energy. Of the four heating sources analysed, district heating was deemed the best.

In both case studies 1 and 3, it is shown that it is possible to identify financially viable renovation concepts; however, doing so should not be taken for granted. For example, the findings from the lifecycle profit analysis in case study 1, show that it was only the combination of energy-efficient renovation and vertical extension which was financially viable. Additionally, the findings from a similar analysis in case study 3 were contradictory, none of the prefabricated multi-active facade concepts were financially viable when applied to the low-rise building, but when applied to the high-rise building, all of the concepts were viable. This again, indicates the importance of assessing each building specifically, the renovation concepts should be fitted to the specific building. Another finding from case study 3, is that just a small differences in either costs or price changes can affect the outcome of the analysis significantly, this demonstrates the fragility of the lifecycle profit analysis. The discount rate in both case studies 1 and 3 were relatively low, if a higher discount rate would be used instead, it would change the outcomes of the analyses drastically. Sensitivity analyses could therefore contribute to a better understanding of the inputs and their potential long-term effects. Together, these findings show the importance of using a method which takes into consideration the whole lifespan of the renovation, all relevant inputs and future changes to these inputs.

6.2 Contributions

At its heart, the research presented here revolves around the decision-making process regarding the renovation of buildings. As previously explained in Chapter 2.2 *Research process*, the research changed course on a few occasions, for the purpose of investigating more aspects of the decision-making process. As such, the four appended papers represent four different aspect to consider in the decision-making process.

The findings in paper 1, show that the combination of energy-efficient renovation and vertical extension was financially viable and could increase environmental performance. This suggests, that researchers need to keep an opened mind when examining less conventional renovation measures, since there might be other measures which could be viable and increase performance.

The development process presented in paper 2 can be tested and further examined by other researchers, as well as, to inspire other researchers to explore development processes for other aspects of construction. For example, a similar development process could potentially be identified for renovation in general or for energy-efficient renovation.

The lifecycle profit analysis presented in paper 3, can be used by other researchers to replicate similar studies and can be adapted to fit their specific study. However, it is highlighted that the results from lifecycle profit analyses are uncertain. Additionally, the method does not guarantee that any of the concepts which seem financially viable actually will be profitable, since any of the inputs used in the analyses could be wrong or change in the near future.

This research links wicked problem theory to construction management, wicked problem theory can be used as an alternative repertoire to assess phenomenon from another perspective. For example, the approached presented in paper 4, where each aspect of renovation is discussed in order to identify if it is wicked or not, could be used by other researchers to study other phenomenon in the field of construction management.

6.3 Further research

As recently highlighted, it would be interesting to examine other phenomenon through the lens of wicked problem theory. This could potentially highlight gaps and weaknesses in the field of construction management. Similarly, a development process similar to the one presented in paper 2, could be explored for other phenomenon. On the other hand, there is potential for improving the presented development process on the vertical extension of buildings; more studies would provide vital critic and depth to the described process. As highlighted in Chapter 5.3, there is a need interpret the output of the lifecycle impact assessment if several factors are assessed. It is far from obvious, which of these factors are to be prioritised over the others or how they should be balanced. In this dissertation and in the reviewed governmental documents, the most discussed factor is that of greenhouse gas emissions. However, since one factor cannot easily be translated into another, it is likely that factor balancing will have to be done on a case-by-case basis in order to get the best result. As the findings from case study 3 show, just small changes to the costs and the price changes can significantly alter the results of the analysis. Therefore, it would be interesting to study how much the costs and price changes can vary. The variations could then be considered in a lifecycle profit analysis using Monte-Carlo simulations to assess the effects.

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Appended papers

Paper 1 – Enabling energy-efficient renovation: the case of vertical extension to buildings

This paper has been published by Emerald Publishing Limited in the journal of Construction Innovation. In this paper, the results from a lifecycle profit analysis and a lifecycle impact assessment from four renovation concepts are presented. The main contribution, is that vertical extensions can enable energy-efficient renovation.

Paper 2 – A development process for extending buildings vertically – based on a case study of four extended buildings

This paper has been published by Emerald Publishing Limited in the journal of Construction Innovation. The main contribution, is the described development process for extending buildings vertically. The development process is based on the success factors and barriers from four cases.

Paper 3 – Lifecycle profit analysis of prefabricated multi-active façades

This paper has been published by Emerald Publishing Limited in the journal of Building Pathology and Adaptation. In this paper, a lifecycle profit analysis of six renovation concepts is presented. The main contribution, is that multi-active façades could be financially viable for renovation projects in a Swedish context.

Paper 4 – Why are we not renovating more?

This paper is a manuscript to be submitted to Construction Management and Economics. In this paper, it is argued that renovations are wicked problems, due to the many complex aspects involved in renovation projects. The main contribution of the publication is the highlighted and discussed aspects and the link to wicked problem theory.