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Building renovation processes towards low greenhouse gas emissions and energy use

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Summary

Large residential areas in Sweden and elsewhere are facing a need for renovation. Swedish buildings from the record year era (1961 – 1974) are now 40 – 55 years old and in many cases in need of extensive renovation measures. This need for renovation could be seen as an important opportunity to achieve overarching sustainability target levels and to perform renovation with a holistic approach. This thesis is part of the research project "*Management of environmental aspects in the renovation process*" aiming at creating support for the formulation and achievement of adequate environmental targets that relate to overarching Swedish Environmental Quality Objectives. The overall aim of the thesis is to contribute to an understanding of the current situation of environmental management in renovation processes. The scope of this thesis is limited to the aspects energy use and greenhouse gas (GHG) emissions from energy use and material production.

This thesis contributes to this aim with a stepwise procedure for evaluation of measures together with a proposal for target levels for three environmental aspects. The three aspects are: *operational energy use*, *GHG emissions due to total energy use for building operation*, and *embodied GHG emissions due to production of building materials*. The first paper appended to this thesis investigates how six Swedish property owners performed renovation projects and how sustainability aspects are handled. From this paper it can be concluded that the way Swedish property owners address environmental aspects in renovation projects needs to be improved. Furthermore, the conclusion can be drawn that the main barrier (except economic ones) are characterized by lack of knowledge about overarching objectives and what aspects define a sustainable built environment.

The second paper assesses embodied GHG emissions due to material production for the totality of measures needed to reduce operational energy demand per unit heated floor area by 50% compared with 1995. On a national level, embodied GHG emissions are estimated to be 12% of the reduction of GHG emissions achieved by operational energy demand reduction. Thus, while embodied GHG emission constitute a relatively small share of the total GHG emissions, the fraction is not insignificant, suggesting that embodied GHG emissions are relevant to consider in renovation projects.

The final paper appended to this thesis uses a case study building to illustrate a working procedure to identify project-specific target levels for the three aforementioned environmental aspects. In addition, it identifies indicative improvements necessary for the achievement of long-term targets for those aspects, which could be focused and further investigated in later project stages or future renovation projects with the help of a long-term plan of action. The final paper also presents an initial proposal for sustainability target levels for the three aforementioned aspects. The overall conclusion from this research is that there is a need for agreement upon which aspects and performance levels should be considered in a *sustainable renovation* project.

Key words: Renovation processes, buildings, energy efficiency, greenhouse gas emissions, target levels

Sammanfattning (Summary in Swedish)

Stora bostadsområden i Sverige och även på andra håll står inför ett renoveringsbehov. Byggnader uppförda under de svenska rekordåren (perioden 1961-1974) är i många fall i behov av omfattande renoveringsåtgärder. Detta renoveringsbehov kan ses som en viktig möjlighet för att genomföra förbättringar som bidrar till uppfyllandet av övergripande samhällsmål och att dessa renoveringar bör utföras med ett helhetstänk. Denna avhandling är en del av forskningsprojekt "*Miljöstyrning i renoveringsprocessen*" som har till syfte att skapa stöd för styrning av viktiga miljö- och hållbarhetsaspekter i renoveringsprocessen och bidra till uppfyllandet av målnivåer som ansluter till de övergripande svenska miljökvalitetsmålen. Det övergripande syftet med avhandlingen är att bidra till en förståelse av den nuvarande miljöstyrningsprocessen. Omfattningen av avhandling begränsas till aspekterna energianvändning och utsläpp av växthusgaser från driftsenergi och inbyggda material.

Resultatet av forskningsprojektet är en procedur för utvärdering av åtgärder samt ett förslag till målnivåer för tre viktiga miljöaspekter. De tre aspekter är: *energianvändning (köpt energi)*, *utsläpp av växthusgaser till följd av totala energianvändningen för byggnaden* samt *inbyggd klimatpåverkan från tillkommande material och produkter*. Den första bilagda artikeln undersöker hur sex svenska fastighetsägare i dagsläget utför renoveringsprojekt och hur hållbarhetsaspekter hanteras. Från denna artikel kan slutsatsen dras att på sättet som svenska fastighetsägare i dagsläget handskas med hållbarhetsaspekter i renoveringsprojekt måste förbättras. Ytterligare en slutsats som kan dras är att det största hindret (förutom de av ekonomisk karaktär) kännetecknas av bristande kunskap om övergripande samhällsmål samt vad som definierar en hållbar bebyggd miljö.

Den andra bilagda artikeln bedömer inbyggd klimatpåverkan från tillkommande material för samtliga åtgärder som krävs för att minska energianvändningen per uppvärmd yta med 50 % jämfört med år 1995. På nationell nivå uppskattas den inbyggda klimatpåverkan motsvara ca 12 % av minskning av klimatutsläpp som uppnås genom minskad energianvändning. Av detta dras slutsatsen att inbyggd klimatpåverkan utgör en relativt liten andel av de totala utsläppen av växthusgaser, men ändå inte obetydlig, vilket indikerar att även inbyggd klimatpåverkan är relevant att beakta vid renovering.

Den sista artikeln som bifogas denna avhandling presenterar bland annat en fallstudie som används för att illustrera en procedur för utvärdering och identifiering av projektspecifika målnivåer för de tidigare nämnda miljöaspekterna. Dessutom identifieras potentiella åtgärder, som krävs för att uppfylla långsiktiga samhällsmål för de aspekterna, dessa åtgärder kan fokuseras på i senare skeden i projektet eller i kommande renoveringsprojekt. Den sista artikeln presenterar också ett första förslag på uthållighetsmålnivåer för de tre miljöaspekterna. En övergripande slutsats från forskningsprojektet är att byggsektorn behöver komma överens om vilka aspekter och vilka prestandanivåer som ska beaktas i ett renoveringsprojekt för att det ska ses som ”*hållbar renovering*”.

Nyckelord: Renoveringsprocessen, byggnader, energieffektivisering, växthusgasrutsläpp, målnivåer

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I am grateful to all the people who, in one way or another, have made this work possible. Firstly, I would like to acknowledge the organizations that have financed this research and with that said I am sincerely grateful to my employer, Bengt Dahlgren AB, which gave me the privilege and great opportunity to become a Licentiate student at KTH Royal Institute of Technology. Secondly, I would like to express my gratitude to colleagues, supervisors, reviewers, and others who have contributed with feedback.

The work presented in papers 1 and paper 3 was carried out as part of the research project "*Management of environmental aspects in the renovation process*." The project was funded by The Swedish Research Council for the Environment, Agricultural Sciences and Spatial Planning (Forskningsrådet Formas) and co-funded by Bengt Dahlgren AB, Botkyrkabyggen, Center for Sustainable Communications - KTH, EDH Sfären, Fastighets AB Seglet, HSB Riksförbund, Riksbyggen, Rotpartner, Sweco Architects, Uppsalahem, and WSP Group.

The work presented in paper 2 was carried out as part of research project *MECOREN—Methods and Concepts for sustainable Renovation*—funded by The Swedish Research Council for the Environment, Agricultural Sciences and Spatial Planning (Forskningsrådet Formas). Björn Mattsson and others at the Swedish National Board of Housing, Building and Planning (Boverket) were very helpful in providing data from the BETSI assessment and made the work in paper 2 possible. I would especially like to thank Nils Brown as the leading author of paper 2.

I am very grateful to Docent Tove Malmqvist, my very knowledgeable and humble main supervisor who has given me all the support and inspiration a PhD student could ever desire. As co-author of all three appended papers, Tove has been very supportive throughout the process. Further, I am grateful to my co-supervisor Professor Göran Finnveden as well as Professor Emeritus Mauritz Glaumann for their support and constructive feedback on the work. I would also like to acknowledge Dr. Joachim Claesson for his valuable comments and feedback as a reviewer of this thesis.

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Preface

It may be interesting for the reader to know something about the researcher's background. After graduating as a M.Sc. in Mechanical Engineering from KTH Royal Institute of Technology in Stockholm in December 2006, with a major in Sustainable Energy Utilization, I began working as an engineer at Bengt Dahlgren AB, an HVAC consulting company. In that role, I spent six years doing things like HVAC-systems design, building investigations, and energy and cost calculations. Then, in February 2013, I got the opportunity to become a part-time industrial Licentiate student at the division of Environmental Strategies Research (fms). Throughout this research project, I have continued to work part-time as an engineer at Bengt Dahlgren AB. By combining research and work as a technical consultant in the building sector, I have had the opportunity to experience different real-life industrial problems and work processes. I think that my industrial experience and my contacts from working in the building sector for more than six years prior starting my Licentiate studies have been very valuable in the planning and realization of this research project. Now I hope that my experience as a Licentiate student and the practical application of its results will become valuable when returning to the industry.

Appended papers

Paper 1:

Olsson, S.; Malmqvist, T. and Glaumann, M. 2015. Managing Sustainability Aspects in Renovation Processes: Interview Study and Outline of a Process Model. *Sustainability*, 7(6), 6336-6352.

Paper 2:

Brown, N. W. O.; Olsson, S. and Malmqvist, T. 2014. Embodied greenhouse gas emissions from refurbishment of residential building stock to achieve a 50% operational energy reduction. *Building and Environment*, 79, 46–56.

Paper 3:

Olsson, S.; Malmqvist, T. and Glaumann, M. 2016. An approach towards sustainable renovation—a tool for decision support in the early stages. *Building and Environment*, 106, 20-32.

Contribution of the author

I am the principal author of paper 1 and was responsible for writing the main structure of the paper. I conducted the interviews, transcribed the answers, and performed the analysis. My contribution to paper 2 consisted of result analysis together with data compilation and spreadsheet calculations, and writing parts of the discussion section and giving feedback on the manuscript as a whole. I am the principal author of paper 3 and was responsible for writing the main structure of the paper. I conducted the case study: its on-site investigation, compilation of building data, calculations, and

analysis. I was also involved in developing the evaluation tool used in the case study; my contribution to that was mainly creation of the constituent measures with the calculation of embodied CO_2-e and costs.

Related publications not included in the thesis

Olsson, S.; Malmqvist, T. and Glaumann, M. 2014. Managing sustainability aspects in renovation processes: interview study and outline of a process model. *Proceeding of the World Sustainable Building Conference 2014 (WSB14)* in Barcelona, Spain.

Olsson, S.; Liljenström, C. and Malmqvist, T. 2014. Miljöstyrning av Renoveringsprocessen: Intervjustudie samt Litteratur- och Projektsammanställning. TRITA-INFRA-FMS 2014:3. KTH Royal Institute of Technology. Stockholm, Sweden. (In Swedish)

Malmqvist, T. and Olsson, S. 2014. Mot en processmetodik för hållbar renovering. *Husbyggaren*, Nr 3, 10-13. (In Swedish)

List of abbreviations

BECEREN	Basic Energy, CO_2 and cost Estimation in Renovation
BETSI	Buildings' Energy, Technical Status and Indoor environmental quality
CEN	Comité Européen de Normalisation
CO_2-e	CO_2 equivalents (carbon dioxide equivalents)
EAHR	Exhaust Air Heat Recovery
EQO	Environmental Quality Objectives
EU	European Union
GHG	Greenhouse gases
GWP	Global Warming Potential
HFA	Heated Floor Area
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life-Cycle Assessment
LCC	Life-Cycle Cost
MECOREN	Methods and Concepts for sustainable Renovation
MFH	Multi-Family Homes
NPV	Net Present Value
RQ	Research Question
SFH	Single Family Homes
SNBHBP	Swedish National Board of Housing, Building and Planning (Boverket in Swedish)
UN	United Nations
UNEP	United Nations Environmental Programme

1 Introduction

At the most basic level, the primary function of a building is to provide shelter for people and their different activities. In terms of dwellings, this means providing shelter with adequate indoor environmental standard such as thermal comfort, air quality, day-light, and acoustic conditions. In the mid twentieth century low housing standards and a shortage of dwellings in Sweden's cities led to a political decision with the aim of eliminating the shortage and supplying people with good quality homes. During the period 1961 – 1975, which is often referred to as the "record years," around 1.4 million dwellings were built. From 1965 – 1974, also known as the "million homes programme," approximately one million dwellings were built. The distribution of the different types of dwellings during the record years is approximately one third of dwellings in single family houses and two thirds consists of dwellings in multi-family residential buildings. This means that approximately 920,000 dwellings were built in apartment blocks. About 35% of the dwellings in the million homes program were built around three of Sweden's metropolitan regions: Stockholm, Göteborg, and Malmö. The remainder was distributed across the rest of the country (Hall and Vidén, 2005).

Some of these 920,000 dwellings in multi-family buildings have been demolished, mainly because of migration from less populated regions of Sweden to the growing metropolitan regions. Approximately 850,000 of the dwellings are still in the housing stock of today and about 600,000 of them remain more or less as originally designed, and half of those are in urgent need of renovation (Hyresgästföreningen, 2015). The buildings are now 40 – 55 years old and in many cases in need of extensive renovation measures such as replacement of plumbing equipment, windows, roofs, and facades. It may be said that this is a "window of opportunity" to achieve overarching societal objectives, not just restoring the original design (Högberg et al., 2009; Kling el al., 2009; Svenfelt et al., 2011; Thoresson, 2013).

In 1999, the Swedish parliament established fifteen Environmental Quality Objectives (EQOs) and in 2005, one objective was added for a total of sixteen EQOs ranging from reduced climate impact to a rich biodiversity. Examples of EQOs related to the housing sector are: A Good Built Environment, A Safe Radiation Environment, A Non-toxic Environment, and Reduced Climate Impact (Naturvårdsverket, 2014). Connected to each EQO are several indicators and milestones. The EQO Good Build Environment includes indicators related to energy efficiency, greenhouse gas emissions, noise, dampness problems, and other indoor environmental aspects and is the EQO that most relates to the housing sector. Besides the EQOs there are other societal goals. One example established by the Swedish parliament is to reduce total energy demand per unit heated floor area by 50% compared with 1995 by 2050 (Miljödepartementet, 2012; Regeringen, 2005; 2008).

Vast renovation needs of building stocks can be seen as a key opportunity to address energy efficiency, climate change mitigation, and social challenges amongst others aspects (EU, 2011b). From a Swedish perspective, this need for renovation is seen as a key opportunity to achieve the

national EQOs (SOU, 2008). To renovate all these buildings in such a way that the objectives are achieved is however a great challenge. But this opportunity will not present itself again for another 40 or 50 years, when it will once again be time to replace for example technical equipment, by then the year 2050 has passed. The integration of long-term sustainability objectives in the renovation processes of today is therefore central.

This thesis was written in light of the need for renovation of the building stock in general, and for renovation of residential buildings from the record year era in particular. In relation to this, the overarching question dealt with in this thesis is how to achieve more sustainable built environment and to facilitate a discussion among practitioners about "necessary" environmental ambitions in renovation projects. This thesis particularly focuses on the renovation processes from a property owner's perspective.

1.1 Integration of environmental concerns in the renovation process

In general, the building design and construction process includes the following stages: strategic definition, preparation and brief, concept design, developed design, technical design, construction, handover, and use (RIBA, 2013). Decisions about the building design are made early in the building design and construction process, typically in the concept design stage. Decisions made in the early stages will govern and restrict further detailed design of the building thus also its environmental performance over its life cycle (Häkkinen et al., 2015; Petersen and Svendsen, 2010; Shi and Yang, 2013; Wallhagen et al., 2011). The building process is similar in both new construction and renovation of buildings. However, in renovation projects, many preconditions and boundaries are already fixed and there are often existing tenants whose opinions also have to be considered.

In contrast to the production of new buildings, renovation projects focused on far-reaching reduction of energy demands together with enhanced indoor environmental quality are only done on a small scale in Sweden (Liu and Thoresson, 2013). Earlier studies have shown that not all profitable energy saving measures is implemented during a renovation project (Granade et al., 2009; Häkkinen et al., 2015). In a Swedish context, it is estimated that only 15% of all profitable measures are carried out (SOU, 2008), although there are debates about the number of measures that are actually profitable and how profitability is calculated (Gluch, 2014; Högberg et al., 2009; SOU, 2008).

Barriers for a broader implementation of renovation processes towards more sustainable buildings have been investigated in studies such as Cattano et al. (2013), Häkkinen and Belloni (2011), and Thuvander et al. (2012). Beyond concerns about high investment costs and problems with profitability, barriers identified in these studies include (amongst other things): lack of knowledge of sustainability aspects and targets, lack of simplified evaluation tools (for decision-making), insufficient knowledge of the existing building, and inadequate coordination between energy saving measures and other measures.

1.2 Sustainable renovation and quantified target levels

The building sector is the largest user of energy in the global economy, the sector accounts for more than one-third of the total energy use and is a significant source of CO_2 emissions (IEA, 2014a). A study based on input-output analysis on the environmental impacts of the Swedish building and construction sector shows that construction and management activities for buildings, including space heating, accounted for roughly 20% of total national greenhouse gas emissions (Toller et al., 2013). Numbers like these are useful in setting a research agenda and for establishing the importance of change in the built environment and how they are used by their inhabitants. However, such numbers have no connection to how much energy is available, what level of use would be sustainable, or the environmental impact of a certain level of use (Pedersen, 2012). Such sustainable target levels are currently missing.

The notion of *sustainable renovation* has emerged to handle and communicate about, renovation projects where the ambition is to upgrade a building towards achievement of central societal objectives. The interpretation of the notion of *sustainable renovation* varies to a high degree from one project to another just as with the concept *sustainable development* which, due to the complex and dynamic character of the concept, has increasingly come to mean many things too many different people (Johnston et al., 2007). Besides environmental aspects and energy performance, there are also several social and economic dimensions included in the concept of sustainability that need to be handled in a renovation project. Examples of social aspects include human health, well-being, and environmental justice (Bradley et al., 2008; Weingaertner and Moberg, 2014). Examples of economic aspects include an acceptable rate of return on invested capital based on life cycle cost, and not increasing rents to a level where households are forced to move out or become dependent on welfare systems (Högberg, 2014; Risholt et al., 2013). Currently there is no coherent conception of the minimum set of aspects to address in a sustainable renovation project. If the societal challenges concerning the quest for a more sustainable built environment are really to be tackled, what would be the relevant target levels for these aspects? Even though overarching objectives exist, such as energy efficiency and greenhouse gas mitigation, it is far from obvious how these objectives should be broken down into targets for individual sectors and further down for specific organizations or even buildings. In the context of the Swedish building sector, this can be seen through the existing gap between what is considered “sustainable” renovation practice and what is necessary in each renovation project for the achievement of long-term societal objectives.

A number of authors have discussed a more multi-aspect definition of the notion sustainable renovation. Thuvander et al. (2012) consider various terms for building changes such as alteration, rehabilitation, refurbishment, retrofitting, and modernization, but refer to the notion of *sustainable renovation* as the ambition to achieve the dimensions of environmental, social, and economic sustainability when making changes to buildings. Högberg (2014) elaborates on the aspects relevant to sustainable renovation in terms of environmental, social, economic, and technical sustainability. Technical sustainability in this case refers to choosing more robust and thoroughly tested technical

solutions before new, untested ones. Mjörnell et al. (2014) introduce a systematic approach for identifying an optimal set of renovation measures based on a number of sustainability criteria, including Life Cycle Assessment (LCA) for environmental aspects, Life Cycle Cost analysis (LCC) for economic aspects, and a set of indicators for social aspects. This systematic approach uses a simplified LCA focusing on primary energy use and global warming potential (GWP) in the production and end-of-life stages. Furthermore, a recent review found 36 projects and 11 tools dealing with various sustainability aspects in the context of renovation of buildings (Olsson et al., 2014). Seven of the reviewed tools included LCC analysis and six tools included some kind of environmental assessment. The environmental assessments in the tools varied from simplified LCAs dealing with a few impact categories for one or two life cycle stages, to the consideration of emissions of gases contributing to climate change due to energy demand for building operation. There are a very limited number of identified tools that include a combination of LCC and LCA approaches.

LCAs of individual buildings are mostly carried out on "pilot cases," or buildings that have been constructed as low energy buildings, indicating that large parts of the environmental impact over a building's life cycle have shifted from the use stage to the production stage (Cabeza et al., 2014; Liljenström et al., 2015). However, the results are highly dependent on the energy mix of the specific location where a study is carried out and where the construction materials are manufactured. LCAs in the context of renovation have not been studied to the same extent. In order to achieve overarching environmental objectives, it is necessary to consider not only energy use and the environmental impacts from that use but also embodied emissions from the production stage. Therefore, it is important to investigate the relation between reduced emissions due to energy savings and embodied emissions due to added materials to achieve the energy savings.

1.3 Aim and scope of the thesis

The overall aim of this thesis is to contribute to an in-depth understanding of the current situation of environmental management in building renovation processes. Furthermore, it aims to demonstrate and apply methods of providing support for decision making in early stages of planning for a more sustainable built environment in general, but specifically with a focus on energy and greenhouse gas emissions (GHG) when renovating multi-family residential buildings. This thesis specifically focuses on the following research questions (RQ):

RQ 1: How do Swedish property owners address sustainability aspects in current renovation processes and what are the main barriers that they encounter in relation to that?

RQ 2: Are embodied GHG emissions important for improved environmental performance in prioritization of renovation measures for reduced energy demand?

RQ 3: What relevant targets should be considered in renovation projects concerning energy and GHG emissions?

RQ 4: How can decision making in early stages with respect to achievement of relevant target levels be supported?

Due to the broad meaning of *sustainable renovation* and sustainability aspects there is a need to delimit the scope of the research. In particular, this is done by focusing on energy use and contributions to climate change (GHG emissions), without considering other environmental impacts. Furthermore, social aspects of sustainability are not included and economic aspects are handled only briefly.

RQ 1 is handled in paper 1 by interviewing six Swedish property owner organizations. RQ 2 is handled both in paper 2 and paper 3; in paper 2 the question is looked at from a Swedish national perspective, and in paper 3 the question is examined by looking at one case study of a multi-family building. Paper 3 also handles RQ 3. RQ 4 is handled through the case study in paper 3.

1.4 Outline of thesis

This thesis consists of a cover essay and three appended papers (Papers 1 – 3). The cover essay summarizes the papers and puts them in context. The first chapter of the cover essay presents a short background, the overall aim of this work, and related research questions. The remainder of this thesis is organized as follows: chapter 2 (Research methods) provides the theoretical context and methods used; the results are summarized in chapter 3 (Results); chapter 4 (Discussion) discusses the findings and limitations of the research; and in chapter 5 (Conclusions), some general conclusions are presented.

1.5 Organizational background of the research

The main parts of this thesis are part of a research project called "*Management of environmental aspects in the renovation process*." The overall aim of the research project was to develop a process model to support formulation and achievement of adequate project-specific environmental targets, which relates to and supports the larger achievement of related Swedish EQOs. The main outcome of the research project was a *process model*. This process model addresses sustainability aspects, including what activities that should be undertaken in different stages throughout a renovation project. The focus in the process model was on the early stages of renovation and follow-up. The study in paper 1 contributed to the understanding of the renovation process and what barriers property owners might face. The findings from paper 1 were used as a starting point for the process model.

Integrated into the process model was a procedure to evaluate building improvement options in an early project stage. To illustrate this procedure, a tool called BECEREN (Basic energy, CO_2 and cost estimation in renovation) was used. The BECEREN tool is designed to be used in early stages to evaluate how different options affect the environmental performance of a building. Paper 3 describes the tool development process and how it was used in a case study illustrating the procedure for evaluating options in order to identify appropriate project-specific target levels and

set up a long-term plan of action. The case study was also used to illustrate parts of the process model.

The work presented in paper 2 was carried out as part of a research project called MECOREN (methods and concepts for sustainable renovation).

2 Research methods

This chapter provides an overview of methods used throughout the research. This broad research area needs to be approached with a wide range of research methodologies, for instance it is not enough to focus only on neither technical measures nor energy use. The following methods and concepts addressed are: Interviews; Action research and Case study; Life cycle approaches; and Literature review.

2.1 Interviews

Structured and semi-structured interviews are methods for data collection via conversations in order to gain insights into and understanding of a specific phenomenon (Lantz, 2007). In interviews, more detailed questions can be asked than in questionnaires, ambiguities can be clarified immediately, and incomplete answers can be followed up with discussion. Other advantages of interviews include the possibility of obtaining detailed information about things like personal feelings, tone of voice, and facial expressions (Kvale, 1996).

In order to obtain an in-depth understanding of current renovation processes, an interview study was performed, which is reported in paper 1. The interviews were performed in a semi-structured way according to Gillham (2005). For paper 1, eight interviews were conducted with a total of ten people at six Swedish property owner organizations. The interviews were performed in order to learn from the organizations and to gain knowledge of current renovation processes, how they address sustainability aspects, and the main barriers that they face. The interviews were to a large extent open-ended.

The organizations were selected in order to obtain a representative sample of the housing sector in Sweden. The organizations represent three important categories of Swedish residential property owners: small and medium-sized private companies, large publicly owned companies, and housing cooperatives. They also represent both growth markets and non-growth markets; due to the urbanization in Sweden, growth markets are here represented by metropolitan regions, while non-growth markets are represented by depopulated regions in the middle of Sweden. Profiles of interviewees and the organization they represent are shown in *Table 1*. The target group in each organization was personnel with environmental expertise. However, in two of the organizations interviews were conducted with respondents who possessed experience from the operating stage of renovation projects. Respondents in the small organizations were the owner and co-owner who have the responsibility for the overall operation.

Seventy interview questions were predefined based on previous experience and studies that identify barriers for handling environmental aspects in renovation projects. All interview questions were sent out in advance so that the respondent could prepare. Before the interview process started, the respondents were given a brief background of the aim of the study. The interviews were performed face-to-face and lasted for approximately two hours each.

The interviews were recorded and transcribed. For the analysis of the results, the transcription was clustered into recurring topics and themes derived from the answers. The analyses were then discussed with all respondents in a group meeting and then formulated as key considerations.

Table 1: *Characterization of organizations and respondents in the interview study, for further details see paper 1 (apartments refer to rental apartments only).*

Organization	Ownership	Characterization of organization	Interviewees
A	Public (municipally)	Large (12,000 apartments)	Construction and Engineering Manager
B	Private	Small (38 apartments)	Owner
C	Private	Small (140 apartments)	Co-owner
D	Private (cooperative)	Large (25,000 apartments)	Environment and Sustainability Manager
			Property Manager + Project Manager
E	Private (cooperative)	Medium (3,500 apartments)	Environment and Quality Coordinator
			Project Manager of Redevelopment
F	Public (municipally)	Large (16,000 apartments)	Environment Coordinator + Project manager

The sample of interviewees in this study is small, but it can claim to be sufficient for the purpose of this specific study since the sample gave a broad understanding for the differences in preconditions among different organizations. The aim of the interview study was to gain understanding about the incorporation of sustainability aspects and related barriers in renovation projects of multi-family buildings, not to map how different organizations perform.

2.2 Action research and Case study

Action research is a research process explicitly and deliberately used as a tool for change, where action and research are integrated. Additionally, it is often seen as an ongoing process rather than as a project limited in time (Elfors and Svane, 2008). Action research generally involves active participation by the researcher with the purpose of influencing the outcome (Robson, 2002). The principle of the action research methodology is to test a theory or process with practitioners (or co-researchers) in real life situations, and then gain feedback from the attempt, modifying the theory as a result of the feedback and trying it out again. One important aspect of action research is that the researcher has the intention of leaving knowledge behind.

As a result of the interview study reported in paper 1, a *process model* for integration of sustainability aspects in renovation processes was outlined. This process model was developed through an interactive process. First, based on interview results, a literature review, and previous experience, a draft version of the process model was made. Second, this draft version was then further developed through a series of face-to-face dialogues, workshops, and group meetings with

different stakeholders. This development process includes elements of action research since action and research were integrated even though no change was achieved in the participating organizations. The second phase in developing the process model was aimed at testing different limited parts of the process model in renovation cases within some of the participating property owner organizations. In the beginning of the project, the intention was to test and develop the process model in a real renovation project. Unfortunately, due to practical considerations, this could not be achieved. Instead, limited parts of the process model were chosen to be tested with a case study, which is presented in paper 3. This case study was a potential renovation project.

The case study methodology focuses on the process rather than the outcome and is defined by interest in individual cases. A case study can be defined as "an empirical inquiry that investigates a contemporary occurrence within a real life context" (Yin, 2009). The "case" that is the object of study should be a complex functioning unit, be investigated in its natural context with a multitude of methods, and be contemporary (Johansson, 2003). Therefore, case studies can be used to investigate specific objects in detail. An advantage with case studies is that it is a quick way to implement research or spread new knowledge in an organization. One disadvantage is that it might be difficult to generalize from a case study, but it depends on the case and how it is chosen (Flyvbjerg, 2006).

The case study methodology is used in paper 3. The analytical process to establish environmental targets and a working direction in the early stages of the renovation process was tested and illustrated with a case study on a residential building, built in 1961, located in Ljusdal in the middle of Sweden. The building comprises 528 m² of lettable area and 720 m² of heated floor area (HFA). The building owner is also one of the organizations that participated in the interview study. Working with the case study included interviewing the property owner, reviewing existing documentation, on-site investigations, and calculations. Of course, it is unsound to generalize from a case study of a single building, and the varying behavior of different building inhabitants adds an extra dimension of complexity to the case. However, the aim of the case study was never to derive generalizable numerical results but rather to develop parts of the process model in its natural context. The case study resulted in perceptive knowledge that was valuable for the development of the process model on how to evaluate building improvement options in the early stages with respect to achieving overarching objectives.

2.3 Life cycle approaches

Life cycle approaches here refer to a methodological framework that aims to assess potential impacts of a product or service over its whole life cycle from "cradle" (resource extraction) to "grave" (disposal). Life cycle approaches can be performed on a single product or service, or be used to compare several products or services fulfilling similar functions.

2.3.1 Environmental life cycle approaches

Life cycle assessment (LCA) is a tool used to assess potential environmental impacts of a product or service throughout its life cycle. The LCA procedure includes four main phases: goal and scope definition, inventory analysis, impact assessment, and interpretation of the results (ISO, 2006). The life cycle usually consists of four stages: raw material acquisition, production, transport and use, and end-of-life disposal (ISO, 2006). Even though the LCA methodology has been standardized, there are still methodological choices that need to be made by the LCA practitioner regarding elements like functional units, system boundaries, and impact assessments. Applying life cycle approaches like LCA is a comprehensive task and there are a number of barriers hindering the broader application of LCA among practitioners. Examples of barriers to implementation in the building sector include its high data demands, high work intensity (thus making it also expensive), and difficulties in understanding, interpreting, and applying LCA results (Bribián et al., 2009; Brick, 2008; Erlandsson and Borg, 2003; Malmqvist et al., 2011). Complete LCAs includes a broad spectrum of impact categories and life cycle stages. However, in this thesis, since only one impact category (GWP) is addressed for one or two life cycle stages, this could be seen as a simplified life cycle approach or an environmental assessment of GHG emissions based on LCA methodology.

Paper 2 is based on a study called "BETSI energy assessment" (BETSI is an abbreviation of Buildings' Energy, Technical Status and Indoor environmental quality) performed by SNBHBP, the Swedish National Board of Housing, Building and Planning (Boverket, 2009). The BETSI energy assessment focuses on measures needed to reduce the operational energy demands of Swedish building stock by 50% by 2050 compared with 1995. The different improvement measures included in the assessment number about 30 and are described in the microdata provided by SNBHBP. The BETSI energy assessment applies some of these measures to each of 1,384 sample buildings representing the residential building stock in Sweden. Each building was assigned an up-scaling factor to represent the share of national residential building stock. Both single family houses and multi-family houses are included. The data set from the BETSI energy assessment contains information about which measure were carried out on which sample building, and how much reduction in energy use each measure contributed. Measures included up to about 50% energy reduction nationwide. To be able to estimate the embodied GWP due to material production for the study presented in paper 2, material requirements for each of the 30 measures in the BETSI energy assessment were calculated with the help of the Swedish price reference manual for refurbishment measures (Wikells, 2010). GWP was then calculated by matching the material inventories with relevant material production processes or products in the Ecoinvent database, v2.2 (Frischknecht and Rebitzer, 2005) and by using the CML 2 baseline 2000 V2.05 impact assessment method (Goedkoop et al., 2010).

Paper 3 describes the development of an Excel-based tool called BECEREN and illustrates its application on a case study building. The BECEREN tool can be seen as an aid to making rough estimations of environmental impacts from building improvements in early project stages,

addressing aspects such as operational energy use, GHG emissions due to total energy use for building operation, and embodied GHG emissions due to material production. The BECEREN tool includes a number of different building improvement options. Options focusing on reducing heat loss through the building envelope have been established in accordance with the Swedish price reference manual for refurbishment measures (Wikells, 2014a) and the reference manual for heating, ventilation, and air conditioning systems (Wikells, 2014b). All measures are described in detail in the tool with price, material requirements, and embodied GHG emissions. GHG emissions are defined in the BECEREN tool as encompassing the CEN 15978 standard (CEN, 2011) modules A1 – A3 (product stage) and B6 (operational energy) only, which could position it as a simplified LCA. In order to calculate the embodied GHG emissions, it was necessary to establish an inventory process for material production. First, a reference unit was established for each measure. The inventory of material requirements for each measure could then be established in accordance with that unit. GWP from material production for each measure was then calculated by matching the material inventories with relevant material production processes in the Ecoinvent database, v2.2 (Frischknecht and Rebitzer, 2005). GWP for a 100-year perspective was calculated using the CML 2 baseline 2000 V2.05 impact assessment method (Goedkoop et al., 2010).

In paper 2, calculations were done to estimate embodied GHG emissions from building materials required to reduce the operational energy demand by 50% nationwide. To get the order of magnitude, the embodied GHG emissions were then related to the GHG reduction due to reduced operational energy demand, based on national average GHG emissions for the prevalent heating technologies in Sweden. In paper 3, an environmental assessment of GHG emission was performed to estimate the embodied impacts from construction materials for building improvement measures for a specific building. Measures considered were only those that contribute to reduce building operation energy in the use stage. With this approach, it is possible to make a comparison between embodied GHG emissions due to material production and GHG emissions from different energy sources for building operation. The studies performed in paper 2 and paper 3 may help indicate whether embodied GHG emissions are significant in terms of improved environmental performance in the prioritization of building improvement options with respect to reduced energy demand.

2.3.2 Life Cycle Cost analysis

Life cycle cost analysis (LCC) is similar to the LCA methodology and provides a framework for specifying the estimated total incremental cost of a product (or a service) during its life cycle (ISO, 2008). In the BECEREN tool described in paper 3, the different improvement options are also evaluated economically from a life cycle perspective. LCC calculations in BECEREN are based on Net Present Value (NPV) (Aniander et al., 1998), and the results are displayed as time to positive cash flow, pay-back time, and investment cost per energy saving. Data about investment costs for each measure were gathered and compiled from Swedish price reference manuals (Wikells, 2014a; Wikells, 2014b).

2.4 Literature review

Consideration of environmental impacts and target steering has become a critical issue within organizations with concern for long-term competitive advantage and sustainable development (Eriksson and Westerberg, 2011). When summarizing identified barriers in paper 1, we recognized a need for quantified environmental objectives for renovation purposes. Throughout the renovation process, there is a need for clarity about the environmental or sustainability aspects to be handled and the performance levels to be achieved. One useful way to identify relevant sustainability aspects and performance levels to address in a specific context is to review, and rely on, consensus documents of significance. A review was performed including policy documents at global, European, and Swedish levels. In the Swedish context, the 16 national EQOs established by the Swedish government provide such a starting point for choosing aspects and developing performance levels (Naturvårdsverket, 2014).

The concept of *sustainable renovation* may include many environmental, social, and economic issues. However, the focus in this thesis is the three aspects listed below (in paper 3 there is an outline of performance levels for these three environmental aspects):

- GHG emissions due to total energy use for building operation,
- embodied GHG emissions due to the production of materials, and
- operational energy use.

Finding the performance levels for these three aspects were based on their relationship to the following criteria:

- approved societal objectives and recommendations, such as consensus documents like the *Sustainable Development Goals* of the United Nations (UN, 2015), the work within EU (EU, 2011a; Dobb et al., 2015), and national EQOs (Naturvårdsverket, 2014),
- concepts like *"Planetary boundaries"* (Rockström et al., 2009; Steffen et al., 2015) and *"A Safe and just operating space"* (Raworth, 2012), which are both concepts from the scientific community with widespread acceptance,
- actual performance requirements—avoiding targets based on means to achieve good performance such as routines,
- specific quantified performance levels—avoiding fuzzy formulations and interpretations, and
- existing assessment and building certification tools.

In order to suggest performance levels for the aforementioned aspects statistics from Swedish authorities were used (Boverket, 2003; Energimyndigheten, 2009; SCB, 2012; 2014; 2016a; 2016b). Calculations were performed in order to quantify relevant performance levels (see paper 3 for more details).

3 Results

3.1 Barriers for a broader integration of sustainable renovation processes

The study performed in paper 1 includes results from an interview study aimed at obtaining an in-depth understanding of renovation processes and how some sustainability aspects were handled by various Swedish property owners. A frequently recurring theme of the interviews was profitability expectancy; almost every decision was affected by expected economic return. When estimating profitability, most of the interviewees said that their organization used some kind of LCC approach, but it greatly depended on the project manager, and some of them used only simple pay-back time estimates. It was also shown that even within the same organization that profitability had been calculated differently depending on the perception and knowledge of the person executing the calculations. One problem that was identified was the lack of overarching guidelines for economic evaluation and what numbers to use. Similar findings are reported by Hochschorner and Noring (2011).

During the analysis of the interviews presented in paper 1, recurring topics and themes occurred, which were condensed into *Table 2*. The table summarizes identified key considerations or barriers regarding implementation of renovation processes for more sustainable buildings. In order to promote more sustainable renovation processes among residential property owners, it is important to deal with these key considerations better.

Table 2: *Key considerations or barriers identified during the interview study in paper 1. (For further details, see paper 1.)*

Area of concern	Key consideration or barrier
Routines and processes	Lack of procedures, checklists etc. for managing sustainability aspects throughout a renovation project from early inspections to procurement of contractors and all the way to follow-up.
	Limited use of environmental programs and plans.
	Lack of energy, environmental or sustainability objectives in maintenance plans and overly modest ambitions for overarching sustainability targets.
	Limited tenant involvement process.
Competence of personnel	Limited engagement or skill of project managers may greatly affect how sustainability aspects are addressed during a project.
	Lack of support for project managers concerning the sustainability aspects to address and the actions to advocate.
	Lack of environmental expertise to support the project team or manager throughout the renovation process.
Environmental performance and energy use	Only limited inspection and evaluation of indoor environmental aspects.
	Lack of detailed analysis of energy performance in early stages.
	Overly general follow-up of both environmental improvements and energy use.
Evaluation of measures	Large differences (even in the same organization) when evaluating the economic and technical aspects of renovation measures.
	Lack of overarching guidelines for input data, such as annual increases in energy prices, useful life of products, inflation etc.
	No consideration of embodied greenhouse gas emissions due to added materials in renovation projects.
Customer satisfaction surveys	Surveys are regularly conducted but seldom include questions about indoor environmental quality.
	No in-depth questionnaires to identify problems with the indoor environment prior to a renovation project.

One important barrier from *Table 2* is that property owners have overly modest ambitions for overarching targets like energy savings. One example of this is the use of targets based on the 2020 objective (i.e., 20% reduction of operational energy demand by 2020); using this target implies that the ambition of 50% reduction of operational energy demand by 2050 will most likely not be met due to lock-in effects since measures such as replacement of windows, façade refurbishment, and replacement of plumbing equipment are normally performed at intervals of 30 – 50 years.

Regarding monitoring energy use, most organizations summarized energy use on the level of total heating and building electricity, this might cause problems with choice of measures and follow-up. Results from the interview study showed that none of the organizations evaluated measures with respect to embodied GHG emissions from added materials when renovating. However, several of the respondents showed interest in considering embodied GHG emissions if there were a simple and accessible tool for the purpose.

The project manager has a central role in a renovation project and the engagement and qualification of that person can significantly affect how sustainability aspects are addressed from the outset and throughout a renovation project. The interview study reported in paper 1 indicates that there is lack

of support for project managers concerning what sustainability aspects to address and what actions to promote. Lack of support and awareness amongst project managers is a key barrier to overcome in order to promote better handling of sustainability aspects in renovation projects.

Sustainable renovation processes need to be characterized by distinct targets in order to plan, implement, monitor, and achieve significant improvements of important aspects. According to the interview study in paper 1, there is a lack of insight and discussion about what aspects to consider and what performance levels are needed in order to consider a renovated building as sustainable.

Therefore, in order to emphasize important aspects in sustainable renovation processes, it was thought that a supportive process model that would systematize integration and effective handling of sustainability aspects throughout the renovation process could be helpful. The considerations and barriers listed in *Table 2* were the starting points for the development of the process model. An outline of the process model is presented in paper 1. Examples of actions recommended in the process model are performing a building investigation, setting up and analyzing energy use, and involving and engaging tenants in the renovation process. The process model also supplies the user with checklists and templates for different actions, as well as illustrative examples of how the suggested actions could be performed. Integrated into the process model is a working procedure for evaluating potential building improvements and formulating relevant but challenging environmental targets in the early stages of a renovation project, as well as outlining a way to identify which measures can be focused on for reaching such targets (further elaborated in paper 3). Using the evaluation tool BECEREN, which encompasses aspects such as GHG emissions, energy demand, and cost, could be one effective way to initiate the working procedure.

3.2 Considering embodied GHG emissions in the context of renovation

The study performed in paper 2 uses a statistical sample of the Swedish residential building stock to evaluate the importance of embodied GHG emissions for renovation for 50% operational energy reduction compared with 1995. Energy saving calculations has been performed by Swedish National Board of Housing, Building and Planning (SNBHBP) and was included in the BETSI energy assessment microdata. The evaluation was done by comparing embodied GHG emissions from material production for needed measures with GHG emission from operational energy reduction. All measures are assumed to be performed at the same time and each measure is assigned an estimated service life, however maintenance was not included in the study. Thirty renovation measures are included, all of which can be considered for each sample building (though in practice not all of these measures are appropriate for every building). The different measures included in the study are: six measures for improvement of foundation or basement; five measures for improvement of external walls; eight measures for improvement of roof; four measures for improvement of windows; four measures for heat recovery from exhaust air; and three different measures for system tuning and control. For a detailed description of each measure, see *Table 1* in paper 2.

Figure 1 shows the average embodied GHG emissions collated for each renovation measure and expressed as a ratio of the average operational energy reduction for the measure (shown on the left hand axis). The right hand axis in *Figure 1* shows an indicative calculation of the ratio of average embodied GHG emissions and reduced GHG emissions due to reduced operational energy demand for each measure, based on national average GHG emissions for operational energy from Mata et al. (2013).

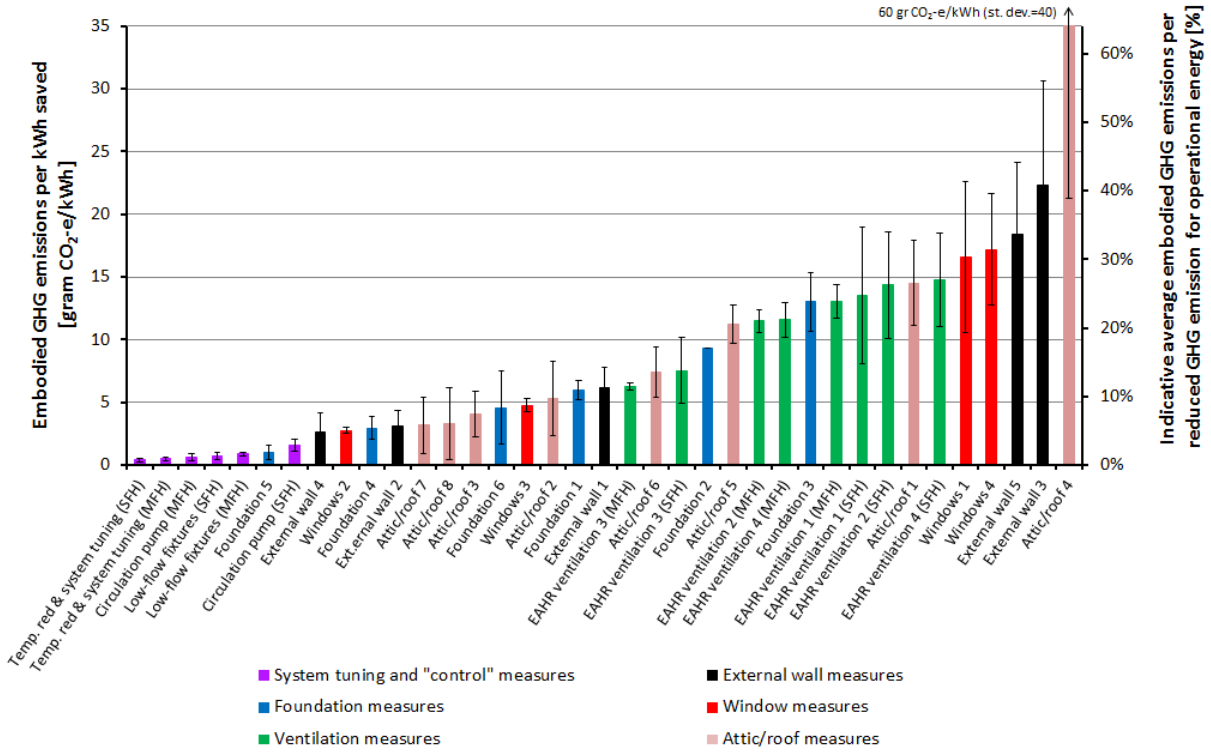

Figure 1: *Average embodied GHG emissions due to material production per unit operational energy demand reduction for renovation measures. Error bars have a magnitude equal to one standard deviation above and below the calculated averages.*

Notable here, when looking at *Figure 1*, is that measures requiring large amounts of mineral-based materials have a significant effect on embodied GHG emissions in relation to other materials. This is shown, for instance, by measures external wall 3 and 5, which both include demolishing an existing brick façade, adding insulation, and replacing with new brick façade, these could be compared with measures external wall 2 and 4 which include other façade materials. *Figure 1* also shows that installation of new window (window measure 1 and 4) has significantly higher impact than refurbishment of existing windows (window measures 2 and 3), assuming that the existing window refurbishment measures do not include retrofitting with external aluminum-cladding (which in reality is quite common). Further, it could be notable that a large number of envelope and ventilation measures have calculated average embodied GHG emissions below 20 gram CO_2-e/kWh

operational energy reduction. Such a value is still low on a life-cycle basis, and this number might be compared with the average production mix of district heating in the whole of Sweden, which is about 89 gram CO_2-e/kWh (Gode et al., 2011).

Overall results of the study reported in paper 2 show that the yearly embodied GHG emissions for all renovation measures required to achieve a nearly 50% operational energy reduction in the residential building stock was 0.35 Mton CO_2-e/yr. The non-annuitized embodied GHG emissions for all measures considered in the study was 9.1 Mton CO_2-e. An earlier study by Mata et al. (2013) looked at energy saving measures applied to the nationwide residential building stock in Sweden. Results derived in that study indicate that a 53% reduction in total operational energy demand corresponds to 2.9 Mton CO_2/yr (i.e., not other greenhouse gases). Results obtained in the study reported in paper 2 imply that on a national level embodied GHG emissions are estimated to be about 12% of the reduction of GHG emissions achieved by operational energy saving. Compared with data from Mata et al. (2013), the environmental "pay-back time" based on the results from paper 2 can therefore be estimated to be just over 3 years. Similar results have also been derived by others, Malmgren and Mjörnell (2015) imply that the environmental pay-back time from applying extensive renovation measures to achieve a nearly 65% reduction in energy demand for a multi-family building is about 3 years. From this, it can be concluded that embodied GHG emissions constitute a relatively small share, but still not insignificant, which suggests that it is relevant to consider embodied emissions not only in new buildings but also for renovation projects.

In paper 3, calculations were done for embodied GHG emissions for 21 renovation measures with a similar methodology as in paper 2. The purpose of making these calculations was to include estimations of embodied GHG emissions in a tool for decision support in early project stages in renovation projects—the BECEREN tool. The BECEREN tool was used in a case study reported in paper 3. Calculations with the BECEREN tool for the case study building in paper 3 indicate that for a 65% reduction in operational energy demand, embodied GHG emissions accounts for about 1.9 ton CO2-e/yr. The non-annuitized embodied GHG emissions equals about 43.2 ton CO2-e, which corresponds to approximately 60 kg CO_2-e/m²(HFA). The annuitized impact from embodied materials accounts for roughly 12% of the total annual GHG emissions (including impact from domestic electricity) after performed measures. This is based on GHG emissions of 344 gram CO_2-e/kWh for electricity (Nordic residual mix) and 33 gram CO_2-e/kWh for district heating (the Ljusdal grid). Total GHG emissions for the case study building does not decrease that much due to the fact that selected measures reduce heating demand greatly but the use of electricity is slightly increased combined with the low impact from heating energy and the high impact used for electricity. This is illustrated by the dotted line in figure 6 in paper 3.

3.3 Environmental aspects and sustainable target levels

The notion of *sustainable renovation* is used frequently in practice and the meaning varies between different actors and different projects; thus the notion has become vague. Knowing what aspects to

include in the notion and what performance levels to target in a renovation project are not straightforward tasks. Furthermore, as indicated in paper 1, there is a lack of knowledge about what would actually have to be achieved for a building to be considered as sustainable regarding certain environmental aspects in relation to overarching societal objectives. To contribute with clarifications about what it actually should implicate in renovation projects there is a need for a set of environmental aspects that might be considered and target levels for those aspects. Such a set of aspects could be seen as a minimum set of environmental aspects to be considered in a renovation project. In order to have a holistic approach when renovating, a broad range of aspects needs to be address, examples of such aspects are elaborated in a report by Malmqvist et al. (in preparation). However, this is not further developed in this thesis which is delimited to three aspects regarding energy and climate.

Three of the aspects elaborated upon in the aforementioned report are included in paper 3, with the aim of suggesting relevant target levels for the Swedish context. The three aspects are: "*operational energy use,*" "*GHG emissions due to total energy use for building operation,*" and "*embodied GHG emissions due to production of building materials*." Energy use is selected because this is an aspect that property owners currently can relate and also have significant influence over. GHG emission due to total energy use is selected because this is an aspect of high priority among policy makers and one important factor for climate change mitigation. Embodied GHG emissions is selected because to is one way to start introducing life cycle thinking in the building sector. Suggested target levels in the Swedish context for these three environmental aspects are presented in *Table 3*. The environmental aspect "GHG emissions due to total energy use for building operation," which includes both operational energy use (bought energy[1]) and domestic energy use, is to be seen as overarching. The reason to consider it overarching is because actions to reduce energy demand can be seen as a means to reduce GHG emissions.

Table 3: *Proposed target levels, in a Swedish context, for three important environmental aspects. (HFA: heated floor area.)*

Aspect	Target level	Unit
GHG emissions due to total energy use for building operation	1.3	Kg CO_2-e/m²(HFA),year
Energy use for building operation	62	kWh/m²(HFA),year
Embodied GHG emissions due to the production of construction materials (added materials)	Derived by the expression: $0.01*(E_B - E_A) + 0.10$, Where E_B is the energy use for the original building and E_A is the energy use after performed measures. 0.01 is a conversion factor.	Kg CO_2-e/m²(HFA),year

[1] Bought energy is a notion used in Swedish regulations for operational energy use of a building where domestic energy is not included (Boverket 2015a).

The proposed target level for GHG emissions due to total energy use for building operation shown in *Table 3* is based on the statement by the Swedish Environmental Protection Agency that the sector "Residential & Tertiary" should reduce its GHG emissions by 90% by 2050 compared with the baseline year 1990 (Naturvårdsverket, 2012). However, even if energy sources with low GHG emissions are used, this is not a reason to use excessive energy. Therefore, it is important to consider operational energy use even though this is indirectly included in the aspect of GHG emissions due to total energy use. The proposed target level for operational energy use in *Table 3* is based on the statement from the Swedish Government that "*total energy use per unit heated floor area of residential and commercial premises should be reduced by 20% by 2020 and by 50% by 2050 compared to 1995*" (Miljödepartementet, 2012; Regeringen, 2005; 2008). By using publicly available statistics from Swedish authorities, the performance levels were calculated. However, the statistics are not fully comprehensive, which means that assumptions and simplifications had to be made.

When implementing measures to reduce energy demand, as a means to reduce GHG emissions, there is a risk that embodied impacts diminish the potential reduction from decreased energy demand. This is why it is important to also consider embodied GHG emissions. However, when formulating targets for embodied GHG emissions for renovation purposes, it is necessary to consider the energy performance before and after performed measure. A target should relate to the amount of material used for reduction of operational energy use. The proposed expression for calculation of the target level (see *Table 3*) relates to the operational energy use of the original building (E_B) and the operational energy use after performed improvements (E_A). The expression is based on the linear regression of twelve different measures plotted in a diagram with reduction of operational energy use on the horizontal axis and embodied GHG emissions on the vertical axis. The target expression is somewhat modified compared with the equation from the linear regression. Measures plotted in the diagram are a selection of measures included in the BECEREN tool applied one by one to the case study building used in the study in paper 3. The measures were selected in order to include building parts covered by the BECEREN tool and to get diversity. For more details about the development of the performance targets for these three aspects, please refer to section 3 in paper 3 and the report Malmqvist et al. (in preparation).

3.4 Procedure to evaluate improvements and support achievement of sustainability targets

Barriers for a broader integration of sustainable renovation processes have been reported in paper 1, from which it could be said that the lack of knowledge about sustainable target levels for environmental aspects such as energy use and GHG emissions is to be seen as a key consideration. The study in paper 1 highlights the need for a working procedure for consideration of aspects like energy use and GHG emissions targets in relation to overarching sustainability target levels, and how to evaluate different improvement options affecting the performance of the building.

In paper 3, a case study building is used to illustrate a working procedure to identify ambitious but realistic target levels for a specific project, which also are related to overarching sustainability targets for the built environment. In addition, it identifies indicative improvements necessary for the achievement of such long-term targets, which could be considered and further investigated in later project stages or in future renovation projects with the help of a long-term plan of action.

Reducing GHG emissions from energy demand is interconnected with the performance of the energy supplier. Therefore, when prioritizing renovation measures, the procedure takes its starting point in energy use. Energy use is something that a property owner has significant influence over, and is also a performance indicator that most property owners currently can relate to, as opposed to GHG emissions (cf. *Table 2*). In order to include aspects such as GHG emissions in the decision-making process, an early stage assessment tool like BECEREN can be helpful. With the help of the BECEREN tool, the achievement of GHG emission targets can be continuously overseen when testing potential improvement options for a specific building. The tool considers both GHG emissions due to total energy use for building operation and embodied GHG emissions due to material production. For detailed description of the BECEREN tool, see paper 3.

In the case study used in paper 3, the first step was to normalize building energy use (e.g., ventilation air flow rate or other comfort requirements) in order to fulfill building regulation or to handle extreme user behavior. The second step was to evaluate different improvement options until sustainable target levels for issues such as energy use were achieved. The evaluation of improvement options could take its starting point in measures that, for instance, have the largest potential to save energy, the greatest improvement of indoor environmental quality, the most economic benefit, or the greatest need for renovation. In the evaluation performed in paper 3, the starting point was measures that had the largest potential for energy saving. The case study building required nine measures to reach the sustainability target for operational energy use (see *Table 4* for details). *Table 4* presents numbers for each specific measure as executed separately. Here it should be noted that the final performance of the building is not the sum of all individual measures since different measures interact and affect the overall heat demand for the building together with the internal heat gains. The final performance of the building is seen on the second line from the bottom in *Table 4*.

Table 4: *Results from the evaluation of measures for the case study building. Domestic electricity not included, which is assumed to be equal to 30 kWh/m²(HFA),yr.*

	Energy		**Emissions**		**Costs**		**Investment**			
	Reduction in energy use		Greenhouse gas emissions		Energy	Main-tenance	Total	Positive cash flow	Pay-back time	Invest-ment per energy saving
			Material production	Mtrl. prod. + operation energy						
	kWh/m², yr	%	$kgCO_2e$/ m²,yr	$kgCO_2e$/ m²,yr	€/m²,yr	€/m²,yr	€	Year	Year	€/kWh
Measure 1	46.5	25.8	0.40	-0.20	-2.44	0.20	31,973	11	20	0.04
Measure 2	15.7	8.7	0.30	-0.22	-0.86	0.00	10,800	0	17	0.05
Measure 3	11.6	6.4	0.47	0.09	-0.64	0.00	51,261	51	112	0.37
Measure 4	19.4	10.8	0.09	-0.55	-1.07	0.00	30,324	21	39	0.06
Measure 5	9.9	5.5	0.30	-0.02	-0.54	0.00	35,341	47	90	0.14
Measure 6	8.6	4.8	0.06	-0.22	-0.47	0.00	2,689	0	8	0.01
Measure 7	1.4	0.8	0.01	-0.03	-0.08	0.00	11,140	51	205	0.31
Measure 8	12.5	6.9	0.14	-0.28	-0.69	0.00	11,792	20	24	0.07
Measure 9	2.3	1.3	0.83	0.05	-0.22	0.00	4,388	26	28	0.13
Final perf.	**62.2**	**65.5**	**2.6**	**11.4**	**4.3**	**0.2**	**189,707**	**34**	**42**	**1.0**
Start. point	*180.1*	-	-	*12.5*	*10.6*	-	-	-	-	

Measure 1: Installation of mechanical exhaust and supply air ventilation with central air handling unit with heat recovery.
Measure 2: Installation of waste water heat exchanger and installation of low flow fixtures in kitchen and bath.
Measure 3: Change of windows, U-value 1.1 W/m²,K.
Measure 4: Additional insulation on outside of exterior wall, 200 mm XPS board.
Measure 5: Additional insulation of basement floor between supporting walls, 200 m XPS board.
Measure 6: Additional insulation of attic, 400 mm loose mineral wool.
Measure 7: Additional insulation on outer side of basement walls below ground, 70 mm XPS boards.
Measure 8: Installation of solar collector system, 20 m².
Measure 9: Installation of PV-cell system, 15 m².

The third step performed in the case study was to check if targets for GHG emissions were achieved. If they were not, other improvements needed to be considered in order to achieve the GHG emission targets (e.g., change of energy supply). However, this was not further explored in the case study reported in paper 3.

All nine improvements combined could be seen as a totality of improvements needed to achieve the sustainability target level for operational energy use by 2050. In order to evaluate relevant project target levels for a specific renovation project of a building, the next step was to evaluate the totality of improvement options from an economic stand point. This was done by ranking the potential measures based on investment per energy saving and determining the profitability requirements in terms of years to positive cash flow. Investment per energy saving can be seen in the rightmost column in *Table 4*. The procedure continued with adding measures one by one, starting with the one with the lowest investment per energy saving until the requirement for years to positive cash flow was exceeded (the profitability requirements could be, e.g., 10 years). By changing the default economic settings, evaluating different future scenarios, and considering alternative funding, it might be possible to include more improvement options within the profitability requirement. Default settings for economic analysis in the BECEREN tool are annual energy price change rate +3% and discount rate of 5%. The improvements included in this step could be looked upon as improvements to be included in a first step of several future renovation steps or regular

maintenance in order to reach the sustainability targets for the building. In the case study illustration presented in paper 3, measures 1, 2, 4, and 6 (cf. *Table 4*) were the ones included in the "first renovation step." Evaluated improvements not included in this first step, but needed for the achievement of the sustainability target level for energy use, could be seen as measures to plan for in future renovation projects of the building. These measures could be part of a long-term plan of action.

The proposed stepwise procedure for evaluation of measures—establishing project specific targets, and creating a long-term plan of action—could be summarized as follows (slightly modified compared to what is presented in paper 3):

1. Check if there are abnormally high energy use or comfort requirements not fulfilled for the building and take actions;
2. Choose improvements until the sustainability target for energy use is achieved, and use default settings for economic calculations. Start evaluating measures to reduce heat loss, then ensure efficient electricity use, and lastly choose an energy source;
3. Rank the potential measures by investment cost per energy saving (€/kWh) and determine the profitability requirements, with some margin, in terms of years to positive cash flow;
4. Choose measures one by one, starting with the lowest investment cost per energy saving from step 2 until the requirement for years to positive cash flow is exceeded;
5. Evaluate how the time to positive cash flow changes by changing the default settings (i.e., energy price development rate and discount rate), and evaluate different future scenarios, and check if additional measures (continue with measures excluded in step 4) can be included in the list of actions with a more favorable economic scenario;
6. Consider alternative funding (e.g., building extensions to increase lettable area or increases in rent) to include additional measures;
7. Check that the sustainability targets for GHG emissions are achieved, and if not, evaluate whether it is possible to implement other actions;
8. Establish project specific targets for the three environmental aspects and a plan of action for future renovation projects.
9. Establish a long-term plan of action for achievement of sustainability targets.

The BECEREN tool (along with the suggested step-by-step evaluation procedure) provides an effective way to evaluate various potential improvement options in early project stages and to get an idea of necessary measures for the future achievement of overarching societal targets. Furthermore, this procedure provides the basis for integration of potential measures in environmental programs, maintenance plans, and long-term management for renovation of the building.

4 Discussion

As pointed out in paper 1, there are several important barriers to overcome for a broader implementation of sustainable renovation processes in order to achieve overarching sustainability objectives. One frequently recurring issue are expected rate of return. If money and profitability have a great influence over decision-making, there are different options to bring about a change, such as; internalization of environmental burdens through taxes on for instance energy use and GHG emission, legal requirements for e.g. certain levels of energy use for certain buildings, or introducing other driving forces of which environmental certification could be one such driving force. Brown et al. (2015) highlights the fact that aiming for a certain level in an environmental certification tool introduced an incentive to include measures that otherwise would not have been considered. According to the interview study performed in paper 1 property owners have a tendency not to include other environmental aspects or measures than the most needed one, environmental certification tools might be one effective way to overcome this.

One important barrier in planning for a more sustainable built environment is the lack of a common view of what aspects and performance levels that could be considered in sustainable renovation processes. In order to achieve a sustainable built environment and to know what targets to consider, it is important to know what aspects to consider and what the distance-to-target is for a specific building. It also means comparability between projects if target values are set as quantified levels. There is an on-going work aiming to identify optimal renovation measures based on a number of sustainability criteria, example of such work is the Renobuild methodology introduced by Malmgren and Mjörnell (2015). A similar approach is the European Retrofit Advisor tool (E2ReBuild, 2016), which aims for a multi-criteria assessment of sustainability aspects for various renovation scenarios. However, none of these tools includes quantified target levels that are considered sustainable for the assessed aspects. In practice, voluntary certification tools such as BREEAM, LEED, and Miljöbyggnad in Sweden provide a more common view of aspects and performance levels among practitioners (Brown et al., 2015). These certification tools are currently becoming more and more popular interpretations or practical definitions of the notion sustainable renovation. However, target levels in the environmental certification tool Miljöbyggnad do not claim to actually be sustainable levels. In Miljöbyggnad, which is the most common certification tool in Sweden, some important environmental issues are missing. Aside from social and economic aspects which should be included in the sustainability concept, one important environmental aspects missing in Miljöbyggnad is climate impact. One useful indicator for climate impact could be GHG emissions assessed as CO_2-e. Mitigating GHG emissions are of high priority for policy-makers globally (EU, 2011a; Naturvårdsverket 2012; UNEP, 2012; IPCC, 2014). To approach the area of sustainable built environment requires a toolkit with a wide range of research methodologies and it takes time to cover all aspects and is not easily done. This thesis focuses mainly on inclusion of energy use and GHG emissions in early design stages.

According to findings in paper 1, aspects including GHG emissions may be considered by property owners if there were a user friendly and reliable tool for the purpose. As described in paper 3, the BECEREN tool is designed to be such an “easy to use” tool, aiming to start making rough estimations of the GHG emissions over the dominating life cycle stages of a building. In order to estimate the reliability of the BECREN tool requires further development and evaluation, one way of doing this could be through feedback from practitioners using the tool. Considering embodied GHG emissions due to added building materials during renovations is becoming more important when buildings getting more and more energy efficient. According to results reported in both paper 2 and paper 3, it may be said that embodied GHG emissions due to production of materials are a non-negligible share of the overall mitigation of GHGs from operational energy demand. The construction stage (module A4 - A5 in the CEN 15978 standard) is excluded in the assessment in both paper 2 and paper 3. According to calculations by Liljenström et al. (2015) the construction process constitutes about 12% of the total embodied emissions in a newly built house (multi-family) which is considered to be a small share compared to the 84% that originates from the product stage, and about 4% of the emissions are related to transport. The construction stage in a renovation project would most probably constitute an even smaller share than for a new construction.

Results derived from calculations in paper 2 and paper 3 justify the approach taken in expanding the environmental assessment of measures for reduced energy demand to include assessment of embodied GHG emissions due to production of materials (or products). Even though the assessments reported in this thesis was intended as screening exercises, it suggests that for high environmental performance of a specific package of renovation measures, it is important to identify manufacturers that have worked actively to reduce the impact of their production by using, for instance, renewable energy sources and recycled materials. Calculating embodied GHG emissions involves many assumptions and methodological choices. Tools like BECEREN, which is used in paper 3, can be helpful in order to overcome methodological choices and assumptions when considering embodied GHG emissions in different renovation projects. Here it may be said that the BECEREN tool only considers the impact category climate change and covers only parts of the different life cycle stages of a product or material. In doing so, there might be a risk of sub-optimizing building improvements, which may have potential environmental impact in other impact categories or in excluded life cycle stages. However, the approach taken here is still seen as a useful starting point for the introduction of life cycle approaches in renovation projects. The BECEREN tool is highly transparent; the user can follow the calculations and change all default values if more accurate values are available, which is seen as an important advantage.

As mentioned previously there is a lack of a common definition of the notion *sustainable renovation*. In practice, the notion sustainable renovation is used by many different actors and the meaning of the notion varies from project to project. In order to contribute to a concretization of the notion there has been a development of three important environmental aspects and proposed sustainability target levels for those aspects. These three aspects are: operational energy use, GHG

emissions due to total energy use for building operation, and GHG emissions due to production of building materials. However, the performance levels presented for these three aspects (see section 3.3 in this thesis) should be further discussed and evaluated. The performance level for the aspect GHG emissions due to production of building materials (embodied GHG emissions) should be considered as a first proposal and needs to be further evaluated with more thorough calculations for buildings of different kind and size, and evaluated in practice which could be done by feedback from actual renovation projects. The suggested target expression for embodied GHG emissions in renovation projects is based on today's practice, and the industries manufacturing these building materials and products should also undergo a transition to low carbon production (EU, 2011a), which implies that a sustainability target level should be significantly lower. Even the target level for the two former aspects might need to be lower since they are based on an average of the whole building stock of Sweden. For instance, cultural heritage values make some measures impossible for some buildings. Therefore, the sustainability target for energy use and GHG emissions due to total energy use for building operation should probably be lower due to the unlikeness that the whole building stock in Sweden will be renovated to the same extent. Furthermore, the proposed target levels have no connection to how much energy may be available or any connection to a global environmental justice perspective. The proposed sustainability target levels should be seen as an initial proposal and will most probably need to be further investigated and refined. One could argue that the ultimate sustainable level of energy performance would be if every building were refurbished to the passive house standard (meaning that heating demand is close to zero). However, from knowing the proposed target level for operational energy use in paper 3, 62 kWh/m²(HFA),yr, an interesting comparison can be made with the proposed Swedish definition of a "nearly zero-energy building," which is between 50 and 80 kWh/m²(HFA),yr bought energy depending on type of building (Boverket, 2015b). From a Swedish perspective, this indicates that the proposed sustainability target level in paper 3 is not unreasonable.

According to findings in paper 1, the project manager has an important role in determining how different issues are handled from the outset and throughout a project. Results in paper 1 also show that most property owner organizations have overly modest ambitions for overarching sustainability targets such as energy efficiency, if any at all. This shows that although long-term climate targets exist on the societal level, it is not obvious that these targets trickle down to specific buildings or projects. The evaluation procedure elaborated in paper 3, in combination with the proposed sustainability targets, may be one effective way to initiate a discussion of "distance-to-target" in individual projects as well as a discussion of necessary policy implications by making long-term climate targets explicit in individual projects. The evaluation procedure takes it starting point in a normalized building which means that the first step is to make sure that the building provides adequate indoor environmental standard in terms of air quality and thermal comfort. This is because creating satisfactory indoor environmental quality surpasses energy saving. From this starting point measures would then be evaluated in order to find out a long-term plan of action for target achievement.

From the case study in paper 3, it is shown that, for a significant reduction in operational energy demand, the sustainability target level for the aspect GHG emissions due to total energy use for building operation could not be achieved. The estimated performance after measures of the case study building was approximately 19 kg CO_2-e/m²(HFA),yr including domestic electricity, this based on the average production mix for local district heating (33 gram CO_2-e/kWh) and with Nordic electricity residual mix (334 gram CO_2-e/kWh). This could be compared to the proposed sustainability level of 1.3 kg CO_2-e/m²(HFA),yr. Adjacent to this there might be other scenarios energy production mixes to be considered. Even with a low-carbon-scenario for electricity (production mix of about 8 gram CO_2-e/kWh (Liljenström et al., 2015)) will yield a performance level of about 1.8 kg CO_2-e/m²(HFA),yr which is much closer to the target level but still not achieved. This example shows that the performance of the energy supplier, and whether average, marginal or actual emissions are used, greatly affects the performance of a building. Furthermore, the calculations also show that there is a need for intervention between property owners and tenants since the domestic energy use could have a great impact on the performance of the building. The performance of the building is dependent on the tenants and the energy mix they use for domestic electricity. However, a single property owner's opportunities to influence productions mixes and energy provider are limited. Energy provider for electricity is however selectable, which is not the case for district heating which is the prevalent heating source for multi-family buildings in Sweden (Energimyndigheten, 2013). Another issue is that tenants often have their own contract with an electricity supplier. The importance of energy production mix and tenants' use of energy could be said to demonstrate the parallel need for policy measures targeting energy supply and the use of domestic electricity. And since the use of domestic electricity is in an increasing trend (Energimyndigheten, 2015), it might indicate that it will become even more important in the years to come.

Compilation and analysis of the energy balance of a building is seen as significant for evaluating and selecting measures for a forthcoming renovation project, for future evaluation of performance, and achievement of overarching objectives. In each and every project, there is a need to discuss on what basis measures are selected. For instance, tenant behavior might be the cause of high energy demand. One has to keep in mind that if this behavioral use is the reason for performing physical measures, it might be changed if tenants are exchanged and the outcome of the measure diminishes (or increase).

Renovation is often a long-term investment and its financial outcome over time depends on energy price development and the discount rate. The anticipated lifetime of components is also an important variable for the outcome of the LCC calculations. Taken together, these three parameters highly influence the decision-making process regarding renovation measures (Bonakdar et al., 2014, Hoxha et al., 2014). As reported in paper 1, one important barrier in addition to the key considerations listed in the paper is the fear of high investment costs and problems with profitability. At the same time, it can be concluded from paper 1 that when estimating profitability,

most of the interviewees said that their organization used an LCC approach, but in what way greatly depended on the project manager. The interview study in paper 1 also revealed a lack of overarching guidelines for input data, such as annual increases in energy prices, and the useful service life of products. The suggested step-by-step evaluation procedure presented in paper 3, together with the BECEREN tool, may provide an effective way to discuss profitability and evaluate different economic scenarios. However, the evaluation procedure is generic and may be used with other tools similar to BECEREN. This generic procedure may be helpful for project managers and other stakeholders in order to unify in what way measures are evaluated and how profitability calculations are performed in early project stages. The BECEREN tool provides the possibility to easily change economic parameters such as future energy price development rates and discount rates. This may initiate another important discussion regarding relevant levels of these parameters when calculating cost-efficiency at project level. It can be argued that required profitability for long-term strategic measures can be lower than for short-term investments, but the common approach in practice, according to results in paper 1, is to use the same discount rate for evaluating both types of investments.

4.1.1 Limitations

Some limitations of this work should be mentioned. This thesis builds upon research on six Swedish property owner organizations and how they handle environmental aspects in the renovation process. Even though these organizations were selected in order to obtain a representative sample of the housing industry in Sweden, the results may not be generalizable for all organizations in the sector. Additionally, this thesis is limited to the conditions that prevail in Sweden. Furthermore, this thesis focuses on multi-family residential buildings with rental apartments. Therefore, the results should be treated accordingly and may not be applicable to other sub-sectors such as commercial or public buildings in which other driving forces and preconditions might exist.

Another limitation to keep in mind is people's different perception of the word "sustainable". In the work presented in this thesis, the words "environmental" and "sustainable" are used more or less interchangeably even though the environment is one part of the sustainability concept. This is mainly because, in the beginning of the research project, important environmental aspects were referred to as *sustainability aspects*, but through discussions throughout the research project, the use of the notion of *sustainability aspects* has evolved to refer to *environmental aspects with sustainability target levels*.

5 Conclusions

The overall aim of this work has been to investigate the current situation of management of environmental concerns in building renovation processes. Furthermore, it was to demonstrate and apply methods to provide support for decision-making in early project stages of planning for a more sustainable built environment by focusing on energy demand and GHG emissions. This chapter presents the main conclusions of this thesis.

From paper 1, it can be concluded that the way Swedish property owners in general address environmental aspects in renovation projects needs to be improved. Furthermore, the conclusion can be drawn that the main barrier (except economic ones) are characterized by a lack of knowledge about overarching objectives and about what defines a sustainable built environment. How environmental goals in each renovation project relate to national targets is not discussed among practitioners. Furthermore, paper 1 show that project managers have a central role and it is concluded that project managers often need support in addressing environmental aspects throughout a project. However, it is far from obvious that property owners will implement sustainable renovation projects even if they have the knowledge and tools to do so. Financial, not technical, aspects constitute the largest barrier. Almost every organization operates according to a profit motive, which means that there is a huge gap between what needs to be done and what is being done under present conditions.

Paper 2 shows that embodied GHG emissions from renovation measures required to reduce energy use by 50% in existing residential buildings compared to 1995 is 0.35 Mton CO_2-e/yr. On a national level this is estimated to be approximately 12% of the reduction of GHG emissions achieved by operational energy demand reduction. The conclusion from this is that embodied GHG emissions from material production are non-negligible even in renovation projects, which suggests that it is relevant to consider embodied emissions not only in new building but also in renovation projects. Calculations in paper 3 shows that embodied GHG emissions as share of the reduction of GHG emissions achieved by operational energy demand reduction could vary greatly depending on the impact of energy supply. Furthermore, from the case study in paper 3, it can be concluded from looking at individual improvement options that some building improvements have the potential to increase total GHG emissions.

From both paper 2 and paper 3, it can be concluded that there is a need to promote sustainability target levels for important environmental aspects in order to start discussing distance-to-target in individual projects. In paper 3, there is a suggestion of three environmental aspects to consider as important to address in renovation projects, as well as a proposal for target levels in a Swedish context. The three aspects are: *operational energy use*, *GHG emissions due to total energy use for building operation*, and *embodied GHG emissions due to production of building materials*.

Paper 3 demonstrates an evaluation procedure that may be an effective way to evaluate building improvement options in an early project stage and thereby support the decision-making process in the continuation of a renovation project. The evaluation procedure also constitutes a tool to create a long-term plan of action for the achievement of long-term societal objectives for energy use and GHG emissions. Another conclusion drawn from the case study in paper 3 is that the performance of the energy system will have a significant impact on the possibility of achieving proposed sustainability target levels for GHG emissions due to total energy use for building operation, which is often outside the scope of a single property owner.

A general conclusion from the research as a whole is that there is a need for agreement upon what aspects and performance levels should be addressed in order for a renovation project to be a *sustainable renovation*.

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