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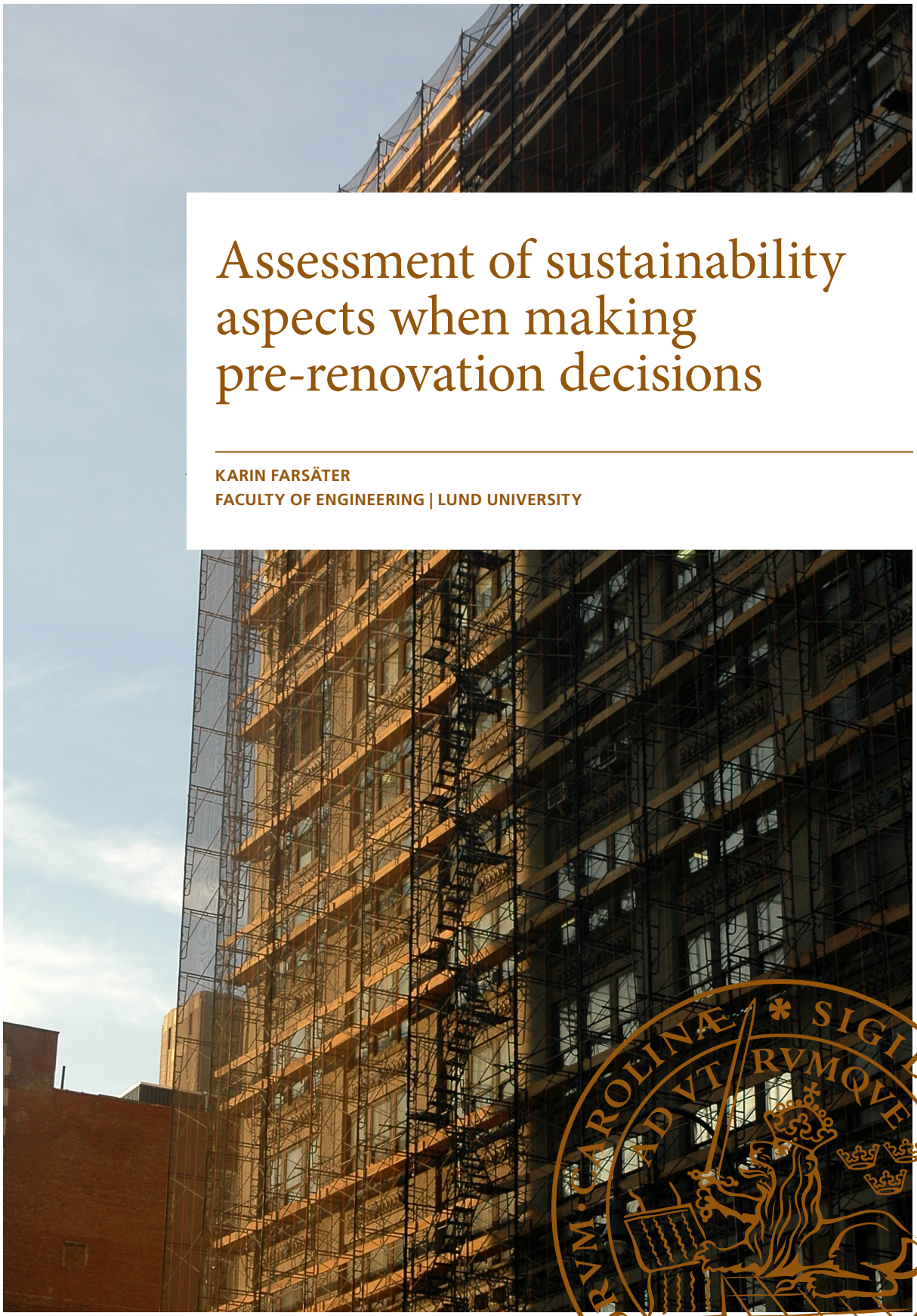
Farsäter, Karin

2022

Document Version:
Publisher's PDF, also known as Version of record



Assessment of sustainability aspects when making pre-renovation decisions

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Assessment of sustainability aspects when making pre-renovation decisions

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LUND
UNIVERSITY

DOCTORAL Thesis

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To be defended at John Ericssons väg 1, the "V-huset" building,
lecture hall V:A, on 30 May 2022 at 1 p.m.

Faculty opponent
Prof. Thomas Olofsson, Umeå University, Faculty of Science and Technology,
Department of Applied Physics and Electronics.

Organization LUND UNIVERSITY	**Document name** Doctoral Thesis
	Date of issue 2022-04-28
Author: Karin Farsäter	

Title and subtitle Assessment of sustainability aspects when making pre-renovation decisions

A considerable amount of Europe's building stock needs to be renovated. The most common reasons for carrying out renovations are acute technical issues or the expiring life span of a building or its components. Other common reason for building owners to carry out renovations in their building stock are high costs for maintenance and operation, and a high energy demand. Furthermore, the construction and real estate sector have been found to be among the greatest contributors to greenhouse gas emissions and energy use and to increase the incentive to renovate the European Union (EU) has a strategy that include the initiative "Renovation wave". Approximately one third of all multi-family buildings in Sweden need to be renovated, especially multi-family buildings and schools constructed during the record years.

The hypothesis in this thesis is "Building owners do not, in a systematic way, take into account and manage sustainability aspects in pre-renovation decisions". The hypothesis was investigated by seven studies that have been carried out by using different methods, such as case studies, surveys, action research, documentation, and literature studies as well as life cycle assessments including scenario and sensitivity assessments.

A review showed that there are several strategies to support decisions of sustainability aspects in a renovation process. The problem does not seem to be lack of strategies but rather the implementation of existing strategies as well as continuous development of the strategies. Therefore, the building owners´ consideration and implementation of a number of sustainability aspects were further investigated. Within the category 'economic aspects', the focus was on energy costs and profitability. For the category of environmental aspect, focus was on energy use and climate change potential. Social aspects mainly included indoor environmental quality, but also other social aspects that came to light during the performed case study.

When analysing previous renovation projects, it was evident that information from earlier renovations was limited. It seems, in these cases, that there is a lack of systematic documentation about how the information before a renovation was generated. Information seems to be missing or linked to an individual person. When following the early phase of a school renovation it was evident how important earlier experiences were. The discussions that were carried out in the early planning phase were, to a great extent, due to the earlier experiences from the included participants. Finally, climate change potential for energy renovation measures was assessed. The results showed that if the energy mix is assumed to change in the future, with less fossil fuel and more renewable sources for electricity, the assessment of energy renovation measures is important to perform.

Based on the results from the performed studies, the hypothesis in this thesis is partly proven. Building owners have started to manage and treat several sustainability aspects in pre-renovation decisions. Methods to consider sustainable aspect of energy use was found to be much more developed than methods to consider aspect such as climate change potential that is in the beginning of the development. A variation of social aspects is treated in different renovation projects but more depending on what is considered to be of importance, than with a systematic approach. However, sustainability aspects are not yet managed in a systematic way. Even though there are several renovation strategies and frameworks with methods and tools available, these are not yet implemented and used in a systematic way by building owners.

Key words: refurbishment, retrofit, life cycle assessment, LCA, climate change, sustainable decisions

Classification system and/or index terms (if any)

ISRN LUTVDG/TVIT–22/1005–SE(203)	**Language** English
ISSN 1652-6783 Assessment of sustainability aspects when making pre-renovation decisions	**ISBN** 978-91-85415-17-5 (print) 978-91-85415-16-8 (e-version)

Recipient's notes	**Number of pages**	Price
	Security classification	

Signature Date 2022-04-28

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Cover photo by Karin Farsäter

Faculty of Engineering
Department of Building and Environmental Technology

ISBN 978-91-85415-17-5 (printed-version) 978-91-85415-16-8 (e-version)
ISRN LUTVDG/TVIT–22/1005–SE(203)
ISSN 1652-6783

Printed in Sweden, Lund University, Lund 2022

I did then what I knew how to do.
Now that I know better, I do better.

- Maya Angelou

Preface

The research for this thesis was carried out at the Division of Building Services in the Department of Building and Environmental Technology at Lund University, Sweden. The work was conducted in close collaboration with four other researchers and three very enthusiastic supervisors. A total of eight individuals, including the author of the thesis, have contributed to the research and its presentation. The work was skilfully guided by my supervisors and all of them contributed with valuable comments. My main supervisor, Åsa Wahlström, contributed with valuable comments both at a detailed level and for the thesis as a whole. I was privileged to have had the opportunity to work closely with Åsa for a long time and if it were not for her, I would not have come this far. My two assistant supervisors, Dennis Johansson and Kristina Mjörnell, together with Åsa, supplied valuable feedback about my work and encouraged its progress by giving their support and sharing their own experiences.

In addition to working closely on this thesis with seven collaborators, the research was conducted as part of a "strong research environment", the SIRen (Sustainable Integrated Renovation) environment, which was founded by Formas, the Swedish Research Council for Sustainable Development, and co-founded by 30 representatives from the building industry. Ten different universities and research institutes are involved in this environment which was established in connection with the National Renovation Centre, NRC in Sweden. NRC was formed in 2013 to promote the increase of knowledge and to spread information about renovation. Knowledge from both academia and the industry is, consequently, collected and disseminated on a broad front. I would like to thank all participants in the SIRen and NRC networks who have inspired me in my work and given me valuable insights from their work and experience.

This thesis was financed through SIRen by Formas and by Boverket, the Swedish National Board of Housing, Building and Planning, within "The potential environmental impact of renovation measures in multifamily buildings in Sweden" project.

I would like to thank my colleagues at the Division of Building Services and the Division of Building Physics in Lund who were greatly supportive during my work on this thesis. Not only colleagues from my own division but also close collaborations with colleagues from other divisions and universities, as well as

collaborations with students, have fuelled my energy and kept me aiming towards my goal.

I am surrounded by understanding family and friends, that have both given me support and the space that I have needed with the comfort of knowing that they have always been there for me.

Karin Farsäter

25 January 2022

Lund, Sweden

Abstract

A considerable amount of Europe's building stock needs to be renovated. The most common reasons for carrying out renovations are acute technical issues or the expiring life span of a building or its components. Other common reason for building owners to carry out renovations in their building stock are high costs for maintenance and operation, and a high energy demand. Furthermore, the construction and real estate sector have been found to be among the greatest contributors to greenhouse gas emissions and energy use and to increase the incentive to renovate the European Union (EU) has a strategy that include the initiative "Renovation wave". Approximately one third of all multi-family buildings in Sweden need to be renovated, especially multi-family buildings and schools constructed during the record years.

Buildings can be seen as our most complex and durable consumer goods. Subsequently, in renovation projects, decision-making is also a complex matter and during the initial evaluation phase of a renovation project it has been seen that there is a lack of time, knowledge, information and tools to make decisions.

The hypothesis in this thesis is "Building owners do not, in a systematic way, take into account and manage sustainability aspects in pre-renovation decisions".

The hypothesis was investigated by seven studies that have been carried out by using different methods, such as case studies, surveys, action research, documentation, and literature studies as well as life cycle assessments including scenario and sensitivity assessments.

First a literature review on different renovation strategies that could support in including sustainable aspects systematically within the areas of economy, environment and social was conducted. The review showed that there are several strategies to support decisions of sustainability aspects in a renovation process. The problem does not seem to be lack of strategies but rather the implementation of existing strategies as well as continuous development of the strategies.

Therefore, the building owners´ consideration and implementation of a number of sustainability aspects were further investigated. Within the category 'economic aspects', the focus was on energy costs and profitability. For the category of environmental aspect, focus was on energy use and climate change potential. Social

aspects mainly included indoor environmental quality, but also other social aspects that came to light during the performed case study.

When analysing previous renovation projects, it was evident that information from earlier renovations was limited. It seems, in these cases, that there is a lack of systematic documentation about how the information before a renovation was generated. Information seems to be missing or linked to an individual person. Systematic feedback and exchange of experience is therefore vulnerable as people change jobs or retire which complicates the transfer of knowledge to future renovation projects. When following the early phase of a school renovation it was evident how important earlier experiences were. The discussions that were carried out in the early planning phase were, to a great extent, due to the earlier experiences from the included participants.

Finally, climate change potential for energy renovation measures was assessed. The results showed that if the energy mix is assumed to change in the future, with less fossil fuel and more renewable sources for electricity, the assessment of energy renovation measures is important to perform. The minimum and maximum variation in materials´ climate change potential show that assessment of different choices of materials should always be carried out before a renovation measure is performed.

Based on the results from the performed studies, the hypothesis in this thesis is partly proven. Building owners have started to manage and treat several sustainability aspects in pre-renovation decisions. Methods to consider sustainable aspect of energy use was found to be much more developed than methods to consider aspect such as climate change potential that is in the beginning of the development. A variation of social aspects is treated in different renovation projects but more depending on what is considered to be of importance, than with a systematic approach.

However, sustainability aspects are not yet managed in a systematic way. Even though there are several renovation strategies and frameworks with methods and tools available, these are not yet implemented and used in a systematic way by building owners.

Furthermore, common for all aspects, there is a need for building owners to adapt the renovation strategies aspect to the conditions of their company and the specific renovation project.

Sammanfattning

En betydande del av Europas byggnadsbestånd behöver renoveras. De vanligaste anledningarna till att man genomför renoveringar är akuta tekniska problem eller en byggnads eller dess komponenters utgående livslängd. Andra vanliga skäl för byggherrar att genomföra renoveringar i sitt byggnadsbestånd är höga kostnader för underhåll och drift samt ett högt energibehov. Dessutom har bygg- och fastighetssektorn visat sig vara bland de största bidragsgivarna till utsläpp av växthusgaser och energianvändning och för att öka incitamentet att renovera Europeiska unionen (EU) har en strategi som inkluderar initiativet "Renovationsvåg". Ungefär en tredjedel av alla flerfamiljshus i Sverige behöver renoveras, särskilt flerfamiljshus och skolor som byggts under rekordåren. Byggnader kan ses som våra mest komplexa och hållbara konsumtionsvaror. Därefter, i renoveringsprojekt, är beslutsfattande också en komplex fråga och under den inledande utvärderingsfasen av ett renoveringsprojekt har man sett att det saknas tid, kunskap, information och verktyg för att fatta beslut.

Hypotesen i denna uppsats är ”Byggnadsägare tar inte på ett systematiskt sätt hänsyn till och hanterar hållbarhetsaspekter i beslut inför renovering”. Hypotesen har undersökts av sju studier som har genomförts med olika metoder, såsom fallstudier, undersökningar, aktionsforskning, dokumentation och litteraturstudier samt livscykelbedömningar inklusive scenario- och känslighetsbedömningar.

Först genomfördes en litteraturgenomgång om olika renoveringsstrategier som skulle kunna stödja i att systematiskt inkludera hållbara aspekter inom områdena ekonomi, miljö och socialt. Granskningen visade att det finns flera strategier för att stödja beslut av hållbarhetsaspekter i en renoveringsprocess. Problemet verkar inte vara bristen på strategier utan snarare implementeringen av befintliga strategier samt kontinuerlig utveckling av strategierna.

Därför undersöktes byggägarnas övervägande och genomförande av ett antal hållbarhetsaspekter ytterligare. Inom kategorin ’ekonomiska aspekter’ låg fokus på energikostnader och lönsamhet. För kategorin miljöaspekt låg fokus på energianvändning och klimatförändringspotential. Sociala aspekter omfattade främst inomhusmiljökvalitet, men även andra sociala aspekter som kom fram under den utförda fallstudien.

Vid analys av tidigare renoveringsprojekt visade det sig att informationen från tidigare renoveringar var begränsad. Det verkar i dessa fall saknas systematisk dokumentation om hur informationen inför en renovering genererades. Information verkar saknas eller är kopplad till en enskild person. Systematisk återkoppling och erfarenhetsutbyte är därför sårbart då människor byter jobb eller går i pension vilket försvårar kunskapsöverföringen till framtida renoveringsprojekt. När man följde den tidiga fasen av en skolrenovering var det uppenbart hur viktiga tidigare erfarenheter var. De diskussioner som fördes i den tidiga planeringsfasen berodde till stor del på de tidigare erfarenheterna från de inkluderade deltagarna.

Slutligen utvärderades klimatförändringspotentialen för energirenoveringsåtgärder. Resultaten visade att om energimixen antas förändras i framtiden, med mindre fossila bränslen och fler förnybara källor för el, är bedömningen av energirenoveringsåtgärder viktig att utföra. Minsta och maximala variation i materialens klimatförändringspotential visar att bedömning av olika materialval alltid bör göras innan en renoveringsåtgärd utförs.

Baserat på resultaten från de utförda studierna är hypotesen i denna avhandling delvis bevisad. Byggnadsägare har börjat hantera och behandla flera hållbarhetsaspekter i beslut inför renovering. Metoder för att beakta hållbara aspekter av energianvändning visade sig vara mycket mer utvecklade än metoder för att beakta aspekter som klimatförändringspotential som är i början av utvecklingen. En variation av sociala aspekter behandlas i olika renoveringsprojekt men mer beroende på vad som anses vara av betydelse än med ett systematiskt tillvägagångssätt.

Hållbarhetsaspekter hanteras dock ännu inte på ett systematiskt sätt. Även om det finns flera renoveringsstrategier och ramverk med metoder och verktyg tillgängliga är dessa ännu inte implementerade och används på ett systematiskt sätt av byggherrar. Dessutom, gemensamt för alla aspekter, finns det ett behov för byggherrar att anpassa renoveringsstrategiaspekten till förhållandena för deras företag och det specifika renoveringsprojektet.

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List of appended publications

Paper I

Literature review on renovation of multifamily buildings in temperate climate conditions

Abdul Hamid, A., Farsäter, K., Wahlström, Å., Wallentén, P.

(Published in *Energy and Building, 2018*)

This study was conducted in a collaboration between the first and second authors with feedback and support from authors three and four.

The literature search in two search engines were divided between the first and second author. The analysis of the found publications and writing of the paper was divided into three sections treating status determination, renovation strategies and renovation measures. The second author conducted the analysis and wrote the background, method and result chapters for the part treating renovation strategies. The papers overall discussion and conclusions were written and formulated by the first and second author. It is estimated that the second author conducted 45 percent of the study.

Paper II

A synthesis of studies on renovation profitability

Farsäter, K., Wahlström, Å., Mjörnell, K., Johansson, D.

(Published in *Proceedings of the 8th Nordic Conference on Construction Economics and Organization* Tampere, Finland 2015.)

(Presented at the conference by first author)

This study was conducted based on an original idea of the fourth author. The first author collected, synthesised and analysed the information for the study. The paper is written by the first author with feedback and support from authors two, three and four.

Paper III

Building status obtained before renovating multifamily buildings in Sweden

Farsäter, K., Strandberg, P., Wahlström, Å.

(Published in *Journal of Building Engineering, 2019*)

The idea for this study came from the SIRen research environment. This study was conducted in a close collaboration between the first and second authors with the support of the third author. The study was conducted with the use of collecting information on performed renovations, questionnaires and interviews. The compilation, questionnaire and interview questions and structure as well as the analysis were developed between the first two authors. The first author conducted all interviews and wrote the main part of the complete paper. It is estimated that the first author conducted 70 percent of the study.

Paper IV

Early decision-making for sustainable school building renovation

Farsäter, K., Olander, S.

(Published in *Facilities, 2019*)

The idea for this study came from the SIRen research environment. This study was conducted in a collaboration between the two authors, who were both involved in following the case study. The gathered information from the case study was complied by the first author. The analysis, from an sustainability perspective, was performed by the first author while the second author made the analysis from an management perspective. The paper was written in a collaboration between the two authors focusing on the different perspectives. It is estimated that the first author conducted 70 percent of the study.

Paper V

Evaluation of Life Cycle Assessment Tools for Assessing the Potential Environmental Impact of Renovation Measures

Farsäter, K.

(Presented at the conference by the author.)

Published in *Proceedings of* iiSBE Forum of Young Researchers in Sustainable Building, Prague, Czech Republic 2019.

The idea was developed within the SIRen research environment through co-supervisor Kristina Mjörnell. The study was conducted and written by the author.

Paper VI

Uncertainty analysis of climate change potential assessments of five building energy renovation measures in Sweden

Farsäter, K., Wahlström, Å., Johansson, D.

(Published in *SN Applied Sciences, 2021*)

The idea for the study was developed by the first author. The study was mainly carried out and written by the first author. The second author contributed with feedback and support and some contribution of specific knowledge from the third author.

Paper VII

Parametric study of reduction of climate change potential through implementation of energy efficient measures in multifamily buildings

Farsäter, K., Wahlström, Å.

(Submitted to *SN Applied Sciences, 2022*)

The idea for the study was developed by the first author. The study was mainly carried out and written by the first author. The second author contributed with feedback and support.

1 Introduction

This thesis is a compilation thesis containing seven published research papers which are two conference papers and five scientific journal papers. The studies have been carried out from August 2014 until December 2022. In this thesis, the seven papers will be presented to show how they have all aimed towards the same goal of assessing sustainable aspects in pre-renovation decisions.

The studies, presented in this thesis, was formed and to a large extent performed within the research environment SIRen. SIRen is a research environment which started in 2014 to create a collaboration platform for researchers and industrial partners to push forward the research on sustainable renovation. This research environment is one example of where the interdisciplinary subject of sustainable renovation has been further developed since the beginning of this thesis. Some of the results from SIRen was published in an anthology that presented studies performed of all different sustainability perspective that are relevant for a sustainable renovation project (SIRen, 2019).

1.1 Background

1.1.1 Renovation

Many of the services and components in existing buildings are reaching the end of their service lives and are in need of renewal and renovation (SABO, 2009; The Swedish National Board of Housing, Building and Planning, 2010). Approximately one third of all multifamily buildings in Sweden are in need of renovations (Johansson, 2017). The most common reasons for carrying out renovations are acute technical issues or the expiring life span of a building or its components (Thuvander, Femenías, Xygkogianni, & Brunklaus, 2016). They concluded that together with high costs for maintenance and operation, a high energy demand is also a common reason for building owners to carry out renovations in their building stock.

According to a survey performed among building owners, it is believed that 50 % of all essential renovations will be carried out within a 10-year period (Johansson, 2017). To achieve this, the yearly renovation rate needs to increase by almost

100 %. The report showed that buildings that were constructed during the 1960s have the greatest renovation needs, closely followed by those built in the 1950s and 1970s.

Between 1951 and 1960, over half a million apartments were built in Sweden (Statistiska centralbyrån, 1975) and during the 1960s and 1970s there was still a great housing shortage in the country. As a result, the *Miljonprogrammet* (The Million Homes Programme) housing campaign was initiated by the Swedish government. Between 1964 and 1975 approximately one million new homes were built (Statistiska centralbyrån, 1975; Swedish National Board of Housing, Building and Planning, 2014). At present, residential buildings constructed before 1970 constitute more than half of the building stocks in several European countries (Meijer, Itard, & Sunikka-Blank, 2009). In Sweden, approximately 70 % of all multifamily buildings were built before 1980 (Hjortling, Björk, Berg, & Klintberg, 2017).After multifamily buildings, the largest category of buildings built before the 1980s in Sweden is schools (Hjortling et al., 2017).. Approximately 74 % of all school buildings were built before 1980. School buildings constitute 17 % of the total non-residential floor area in Europe (Economidou et al., 2011). A study of school buildings in Sweden shows both high energy uses and problems with the indoor environment (Planning & Swedish Energy Agency, 2007). The indoor environmental issues that were reported concerned problems with moisture, thermal climate, indoor air quality, lighting, noise, radon, legionella and cleanability. It is a fact that a good indoor climate is essential for an effective learning environment (Barrett and Zhang, 2009) and there is a pressing need for renovation of school buildings in Sweden (The Swedish National Board of Housing, Building and Planning, 2009).

Buildings are our most complex and durable consumer goods (Lichtblau 2014). Subsequently, in renovation projects, decision-making is also a complex matter. During the initial evaluation phase of a renovation project there is often a lack of time, knowledge, information and tools (Olsson, Malmqvist, & Glaumann, 2015; Thuvander, Femenías, Mjörnell, & Meiling, 2012). Swedish authorities have identified the lack of knowledge, resource and economic constraints as barriers when aiming to improve energy efficiency in renovation projects (The Swedish National Board of Housing, Building and Planning, and the Swedish Energy Agency 2015). Each aspect of a renovation project needs to be evaluated not only on its own but also as an integral part of a larger whole (Kohler & Hassler, 2002; Thuvander et al., 2012). The complexity of managing the building stock is discussed by Kohler and Hassler (2002), both in relation to the different views put forward by the different disciplines involved and to the different issues that need to be considered for a building. Kohler and Hassler (2002) emphasize the importance of the interrelationships between the different aspects of the management of the building stock from a sustainable development perspective.

Renovation as a concept

Many different concepts are used to describe a change to or an update of a building (Mansfield, 2002; Thuvander et al., 2012). Renovation, retrofit and refurbishment are three of the concepts that are sometimes interpreted as being the same. According to the Oxford Dictionary, 'renovation' is part of the definition of 'refurbishment', and 'refurbishment' is a synonym for 'renovation' (Oxford University Press 2016).

- Renovation – "The action of renovating a building." (Oxford University Press 2016)
- Refurbishment – "The renovation and redecoration of something, especially a building." (Oxford University Press 2016)
- For the expression 'retrofit', the Oxford Dictionary defines it as adding something (e.g. component or accessory), in this case to a building.

In the Swedish building regulations, the word 'renovation' is not used (Helsing, 2016). Instead, there are definitions for the Swedish terms for 'alteration, 'reconstruction', 'extension' and 'maintenance'.

- Alteration – measures to change a building's function, construction, usage, appearance or cultural values.
- Reconstruction – the whole or a significant part of a building being modified to a considerable extent.
- Extension – an add-on to an existing building.
- Maintenance – measures to maintain or restore a building's function, construction, usage, appearance or cultural values.

Different terms used in research for measures carried out on existing buildings are discussed by Thuvander et al. (2012). The definitions leave room for interpretation. The term 'renovation' is used throughout this study. As the word 'renovation' is not used in the Swedish building regulations and considering the definition in the Oxford Dictionary, a broad usage of the word is adopted in this study, as it also was by Meijer et al. (2009). The term 'renovation' in this study:

- Refers to a measure that is considered a long-term investment.

Includes measures that restore or improve a building's original function and values.

1.1.2 Sustainability

The common definition of sustainable development was formulated in 1987 in the report "*Our common Future*" (U.N. World Commission on Environment and Development, 1987); "*Sustainable development is development that meets the needs*

of the present without compromising the ability of future generations to meet their own needs". It was, and still is, an important definition for a common conceptualisation of 'sustainable development'. Even after "*Our common Future*" was published it is still not clear what this expression means in practice and how sustainability can be achieved (McKenzie, 2004). The definition gives some answers, but also raises a number of questions. The United Nations Development Programme includes 17 goals to focus on in order to achieve sustainable development (United Nations Development Programme, 2017). One of the goals, no. 11, is 'Sustainable cities and communities'. With an increasing number of people living in urban areas, the importance of sustainably developing these areas is growing.

This section does not aim to present a wide definition of sustainability but to give the reader an understanding of how the concept of sustainability has been used in the context of renovation in this thesis, and how broad the concept is. Sustainability and how sustainability aspects are taken into consideration vary within the building industry (McKenzie, 2004). Sustainability is a broadly used term and needs to be defined wherever it is used. Different actors involved in the renovation process have different perspectives concerning the process and, therefore, have different needs for knowledge. When aiming for sustainability, interdisciplinary understanding is a key factor. Not only is the integration of different aspects, such as environmental, economic and social issues, of great importance but also the integration of the different disciplines within each aspect. The differences in perspective and level of detail in each aspect influence the outcomes when sustainability is taken into account (Wilkinson, Remoy, & Langston, 2014).

Even if there were a clear definition of what sustainability in a renovation means, there would still be uncertainties regarding the levels that each renovation would need to achieve to fulfil the demands set for a particular country or region (Olsson, Malmqvist, & Glaumann, 2016). Due to the uncertainties concerning the term 'sustainability', it will here be treated as a concept to be used when comparing different options, where an option could lead to 'a more sustainable renovation' rather than the more exact term 'a sustainable renovation'.

When narrowing down how sustainable renovation has been used in earlier studies connected to building renovation projects a number of differences in the use of the expression 'sustainable renovation' can be seen. For example, a study from the Technical University in Istanbul evaluated sustainability from two aspects, environmental and economic (Cetiner & Edis 2014). An upcoming standard in Austria for evaluating sustainable buildings states that environmental, social, economic, functional and technical aspects need to be taken into account in order to achieve a holistically sustainable evaluation (Kreiner et al. 2014).Kohler and

Hassler (2002), specifies sustainable aspects to concern economical, ecological, social and cultural issues.

The aspects of life-cycle cost (LCC), energy, indoor environmental quality and hazardous materials were treated by Brown et al. (2013). The term 'sustainability' in their study describes a method that involves more than "simply long-term environmental performance" (Brown et al. 2013). It also states that the purpose of using the term 'sustainability' is not exclusively to give it a definition. The Rebo strategy was developed with the aim of including cultural and architectural values in the sustainability concept (Thuvander & Femenías, 2014). Rebo found seven main categories of aspects, with two levels of sub-categories, to take into consideration. The main categories were described as follows: general, architectural, cultural, social, technical, environmental and economic. These encompass a multitude of different disciplines whereas the sub-categories vary in degrees of development. In this earlier project it can been seen that achieving sustainable renovation is a multidisciplinary and integrated process. The diversity of the aspects that are included in the concept of sustainability and how the different aspects are categorised in main categories and sub-categories is evident in the studies.

The complex issue of sustainability in renovations requires different levels of detail. A well-known overall categorization of sustainability aspects covers three areas: environmental, economic and social issues (Sachs, 2015; United Nations, 1987; Wilkinson et al., 2014). Where the building industry is concerned, studies have added two more main categories, namely cultural and technical issues. Due to the complexity of the concept of sustainable renovation, there is a clear risk of overly complicating the explanation of the concept and this could create an obstacle when applying it to the building industry. Therefore, the general perception, already conceptualized of sustainable aspects (environment, economic and social) will be used as a base in this thesis and will be further adapted for application to renovations. Such as cultural values of a building are considered to be included in the social aspects while technical values need to be considered in all three main categories. The aspect of the energy use of a building is a sub-category of both the environmental and economic aspects.

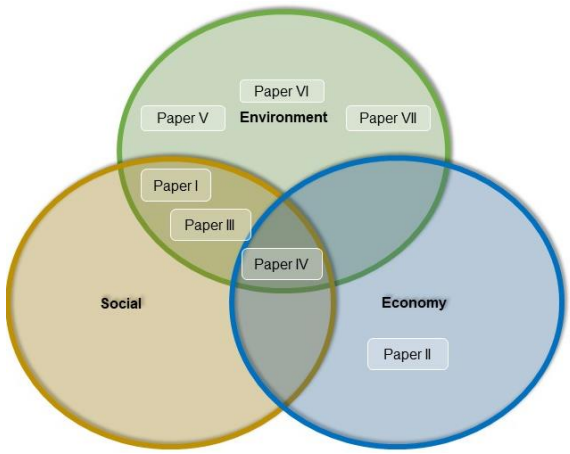

Figure 1: Sustainability aspects investigated in the different papers.

In order to carry out this present study, a number of sustainability aspects were chosen to be focused on. Within the category 'economic aspects', the main focus was on energy costs and profitability, presented in Paper II. The only environmental aspects that were included in the study were energy (included in all Papers) and climate change potential (Papers V-VII). Social aspects, such as indoor environmental quality and user involvement, were discussed here as well as other social aspects that came to light during the course of the study, and these are presented in Paper IV. Some sustainability aspects, for example organisational issues, were not treated in this study, as they were beyond its scope. These aspects, however, are not of any less importance when aiming for sustainability in renovation projects. Figure 1 shows how the Papers in this thesis have investigated the different categories of sustainability aspects.

Environmental aspects

To fulfil the Swedish national environmental quality objectives for a non-toxic environment, the use of hazardous materials, both from an environmental and human perspective, needs to be reduced and decontamination of existing toxic materials needs to be increased (Swedish Environmental Protection Agency, 2016). In the existing building stock (built before 1985) in Sweden, the hazardous toxins radon, PCB, asbestos and freons are present (The Swedish National Board of Housing, Building and Planning, 2010). Nearly half of the multifamily buildings have high levels of radon, approximately 17,500 buildings contain PCB. Asbestos is present in approximately 40 percent of single-family buildings and approximately 50 percent of multifamily buildings. Freons are more frequent in public buildings (16 %) than in multifamily buildings (8 %).

The Swedish national environmental goals also aim for efficient use of natural resources, lower energy use, an increase of renewable energy sources, and energy sources with low environmental impact (Naturvårdsverket, 2021). The national goals are based on the global Sustainable Development Goals (United Nations Development Programme, 2017). In the European Union the goal was set to increase renewable energy sources to 20 percent of the total energy use (Eurostat, 2022). This goal was reached both on a European level and in Sweden.

It is not only the energy demand in buildings that need to be considered when it comes to the existing building stock. To achieve sustainable development all environmental, economic and social aspects need to be included in renovations (European Parliament, 2012). The European Union´s strategy, "Renovation Wave" was proposed to simulate renovation of all buildings in Europe (European commission, 2020). In the strategi, the goal is to lower the energy use and the greenhouse gas emissions from our existing buildings but also to increase job opportunities and increase the indoor thermal comfort.

Approximately 30 % of the Swedish building stock is in need of energy efficiency measures (Johansson, 2017). The building stock accounted for 34 % of the total energy use in Sweden in 2019 (Boverket, 2021). In Europe, the building sector accounts for 40 % of the energy needs and causes 36 % of the greenhouse gas emissions (European commission, 2021) which, potentially, can impact our climate. In an attempt to reduce this risk of impact, goals have been set for all sectors. The aim of the European Union is to be climate neutral by 2050, which will mean including existing buildings that constitute 85 % of the total building stock. Since the construction and real estate sectors have been found to be among the greatest contributors of greenhouse gas emissions and, therefore, are seen as an important sectors in which energy performance must be improved (Eurostat statistics, 2018).

The energy efficiency aspect of building renovations is a sustainability factor that has been researched in several projects as concluded in Paper I Also performed energy efficient renovation measures have been studied (Janson, Berggren, & Sundqvist, 2008). The study showed both renovation projects where individual energy efficient measures and multiple renovation measures had been performed to achieve a larger energy use reduction. As an example, in Sweden, there is a large network of building owners called BeBo that was founded in 1989 and is financed by the Swedish Energy Agency (BeBo, 2020). The main aim of BeBo is to reduce energy use in multifamily buildings in Sweden and to reduce their environmental impact. This is carried out by providing methods to be used during the process of a renovation and showing cases of performed renovation projects (Högdal, 2013; Snygg, Levin, & Falkelius, 2014).

The assessment of the environmental impact of energy use, energy sources and material production can be conducted using different environmental indicators, e.g.

primary energy consumption, global warming potential, ozone depletion potential, acidification potential and eutrophication potential (Forsberg & von Malmborg, 2004; Thuvander et al., 2012). These indicators also form parts of the 16 Swedish national environmental quality objectives.

The standardised life cycle assessment (LCA) method assesses the environmental impact of a product or a service throughout its life cycle (EN ISO 14044:2006). One application of the method is the evaluation of the possibility of reducing the environmental impact. In different research projects, LCAs have been used to assess the environmental impact of different packages of renovation measures on the existing building stock (Itard & Klunder, 2007; Mourão, Gomes, Matias, & Niza, 2019; Olsson et al., 2015, 2016; Ramírez-Villegas, Eriksson, & Olofsson, 2019; Valčiukas, 2012; Vilches, Garcia-Martinez, & Sanchez-Montañes, 2017). In previous studies, the life cycle stage modules A1-A3 (production) and B6 (operational energy use) were identified as being the most relevant stages to assess when it comes to renovation measures (Vilches et al., 2017). The LCA method was used to carry out comparative studies of different renovation options in which the impacts of the materials in modules A1-A3 were compared to the impacts of energy use in module B6. Even though the aim of energy efficient renovation is to decreased energy use in buildings it leads to an increase of material use due to the energy renovation measures which makes it relevant to assess the differences in environmental impact between modules A1-A3 and B6 (Vilches et al., 2017). With decreasing energy demands in buildings, the environmental impact for material productions have become more important to consider (Dutil, Rousse, & Quesada, 2011). So also, the choice of energy source, primarily aiming to increase the use of renewable energy sources and decrease fossil-based fuels must be considered.

Using LCA as a method presents itself with a number of sources for uncertainties, for example, cumulative effects of model imprecisions, input uncertainties and data variability (Swedish Institute for Standards, 2006). There is also an uncertainty in the results of an LCA since most LCAs do not take into account location and point in time of the environmental impacts (emissions). Lately, several studies have been carried out that show the effects of the uncertainties. For example, the Scrucca *et al.* (2020) study shows that variations in results could be due to the person carrying out the LCA. Another study shows that the choice of software and database can influence the results even when LCAs are carried out by the same person (Emami et al., 2019). Furthermore, in LCA studies of newly constructed buildings, the impact of the choice of life cycle inventory database (LCI data), system boundary definition, replacement scenarios and building reference period were analysed by Häfliger *et al.* (2017). They concluded that the choices made when carrying out an LCA study can have significant impacts on the results. In the comparisons of different sources of LCI data for a whole building, they found an approximately 20 % difference between the results when using LCI data from different databases.

Similar conclusions were drawn by Morales *et al.*, (2020) when assessing different painting and plastering options for a brick building.

In earlier studies, when LCAs were used, sensitivity analysis was also included. In a study of a whole building, one which had fulfilled the passive house criteria, it was concluded that sensitivity analyses were applicable for inclusion in the context of an LCA (Pannier, Schalbart, & Peuportier, 2018). In the study, different types of sensitivity analysis methods were tested. This conclusion was further supported in an analysis of the embodied energy of building materials, using an improved method for sensitivity analysis based on Monte Carlo simulations (Pomponi, D´Amico, & Moncaster, 2017). There are two main approaches to performing a sensitivity analysis and these entail either a parametric study or a regression study (Groen, Bokkers, Heijungs, & de Boer, 2017). In a parametric study the input value of one parameter is varied by setting alternative values and carrying out a single assessment per chosen input value. In a regression study, one main minimum and one main maximum value are set for each parameter as well as a distribution. Detailed sensitivity analyses of the influence of uncertainties in LCI data for individual energy renovation measures are lacking in earlier studies. Consideration of the uncertainties of LCI data and carrying out Monte Carlo simulations are not assessed in detail for individual energy renovation measures.

From 1 January 2022, a climate declaration must be provided for new buildings in Sweden before they can be taken into use. The declaration must state the climate change potential of the building´s envelope, its load-bearing structure and all interior walls during the production and construction stages of the building. This is seen as a possible way both to increase awareness of the impact of climate change potential of our buildings and to gather data regarding appropriate levels of greenhouse gas emissions for future regulations. This is seen as a first step in a continuous evaluation of buildings potential impact on the climate. The Swedish national board of housing, building and planning has been commissioned in 2022, by the government to investigate the possibility of introducing climate declarations for building alterations, reconstructions and extensions (The Swedish National Board of Housing Building and planning, 2022).

In a climate declaration, the environmental category that must be included is the climate change potential of the building, in other words, its levels of greenhouse gas emissions. Some materials, however, bind greenhouse gases, biogenic carbon, during different parts of their life cycles. For example, trees bind biogenic carbon during the growth of the raw material (A1 stage). This type of biogenic carbon should, according to SS-EN 15804:2012+A2:2019, be presented separately of the results of climate change potential.

Paper I, the literature review, includes environmental aspects that were found in earlier research, such as energy efficiency and environmental impact. The

environmental aspect of energy is also included in Papers III and IV. In Papers V-VII environmental impacts, more specifically climate change potential, are further assessed.

Economic aspects

The economic aspects of a renovation project can be divided into two categories, i.e. the financing of the project and the making of realistic predictions of the profitability of the project (Lind, 2014b). Other aspects, such as energy prices and socio-economic measures such as employment rates, affordability and rent increases, could also be included in the economic aspects.

The need to discuss the different calculation methods and input data that could be used for profitability calculations is evident in several projects (Högdal 2013). Several methods can be used, such as payback time, net present value (NPV) and lifecycle cost (LCC) (Byman & Jernelius, 2012; Lind, 2014b).

The input data required for a profitability calculation depends on the calculation method. Even with a clear methodology, the calculations rely on realistic input values, for example, for energy prices and lifespans. Papadopoulos et al. (2002) analysed the high impact of energy price changes on profitability calculations. In 2009, energy prices were too low in China for energy efficiency measures to be profitable according to Ouyang et al. (2009). Energy efficiency measures would not be profitable if increases in energy prices were assumed to follow the same trend in the future (Bonakdar, Dodoo, & Gustavsson, 2014). The effect of the different lifespans that were considered, 40, 50 and 60 years, had a small or even negligible impact on the starting point from a life cycle perspective.

Profitability can be calculated from the perspectives of companies or communities (Byman & Jernelius, 2012). A company's calculations can be performed regarding costs, expected income and invested capital. In addition to many company perspectives, socio-economic calculations also include social benefits. Social benefits include, for example, reduced unemployment as well as lower rates of criminality. The use of local work resources can also be taken into account (BeBo, 2016). A tool for calculating profitability was developed by BeBo (the Swedish Energy Agency's client group for energy-efficient apartment buildings) and has been kept updated since then. Socio-economic aspects should, according to the BeBo profitability calculation, always be taken into consideration.

Economical aspects of a renovation, in terms of profitability, are included in Paper II and to some extent in Paper IV.

Social aspects

In this thesis, the social value of a renovation of a building covers a wide range of aspects. The common denominator for social aspects is that they affect both the users of the building as well as the community (Thuvander & Femenías, 2014). With the definition of sustainable development in "*Our common future*" formulated from the perspective of human needs, social aspects provide convincing reasons for renovating the building stock. Human needs are specified in different studies, such as in McKenzie who specifies key needs such as health, education, transport, housing and recreation (McKenzie, 2004). Basic needs also include issues such as justice, trust, civic participations, and fair living standards (Mjörnell, Boss, Lindahl, & Molnar, 2014).

From a societal perspective, Lind (2014a) included social sustainability aspects in a profitability assessment for a renovation of a multifamily building. The aspects included were: effects on crime, effects on employment, acceptance of higher rents, and subsequent effects on neighbouring areas.

In the RenoBuild (Mjörnell et al., 2014) renovation decision support tool, a total of 22 social aspects were categorized by the City of Gothenburg (Göteborgs stad, n.d.; Molnar, Mjörnell, & Eneqvist, 2015). These were: 'a cohesive city', 'social interaction, teamwork and meetings', 'a well- functioning everyday life', 'identity and experiences', 'health and green urban environments', 'safety, security and openness'.

The indoor environmental quality (IEQ) is of great importance for the users of a building (Jaggs & Palmer, 2000). Indicators for IEQ are: humidity, thermal comfort, indoor air quality, noise and acoustics, daylight and solar conditions, electromagnetic fields, tap water quality, and safety and security (Jaggs & Palmer, 2000; Malmqvist, 2008). When presented as an environmental aspect, the use of hazardous materials does not only impact the environment but also the indoor environment (Swedish Environmental Protection Agency, 2016).

To include architectural and cultural historic values in a renovation process, the Rebo project developed a special model (Thuvander & Femenías, 2014).

Indicators for social sustainability are more difficult to quantify than economic and environmental indicators and need to be developed for that particular purpose (Lind & Lundström, 2008; McKenzie, 2004). As a renovation project is interdisciplinary, the social aspects need to be both project-specific and cover a multitude of areas. Social sustainability aspects differ between different renovation projects depending on the needs and issues of the specific projects and their users.

As social sustainability is about people, limiting this concept to specific aspects would make this goal difficult to achieve. In this thesis, the aspect of social sustainability is not quantified but is identified where it was found to be present.

Social aspects such as indoor environmental quality, cultural values and user involvement in multifamily buildings were included in Papers I and III and social aspects of a school building renovation are treated in Paper IV.

1.2 Research gap

Sustainable aspects need to be taken into account by building owners at an early stage of a renovation (Kohler & Hassler, 2002). If different aspects of sustainability can be considered early on in the decision stages before carrying out a renovation, the risk of negative consequences will be reduced. There are examples, where sustainable aspects have been considered in research projects on renovation measures (Balaras, Ph, Dascalaki, & Kontoyiannidis, 2004; Brown, Malmqvist, Bai, & Molinari, 2013; Clinch, Healy, & King, 2001; Gustavsson & Elander, 2015; Hamilton, Steadman, Bruhns, Summerfield, & Lowe, 2013; Jaggs & Palmer, 2000; Malmgren & Mjörnell, 2015) but it has previously been shown that building owners do not generally include sustainable targets in their maintenance plans for their buildings (Olsson et al., 2015). In a compilation study it was shown that several case studies have been theoretically investigated to assess the energy saving potential of different renovation measures but, only a small number of renovation cases that had been carried out involved energy efficiency measures (Jarnehammar, Kildsgaard, & Prejer, 2011). In recent years, there have been a number of initiatives from the Swedish energy agency with the aim to drive the transition towards energy efficiency of the multifamily building stock, such as the "Halvera Mera" and "Rekorderlig Renovering" projects initiated by BeBo (BeBo, 2013; Högdal, 2013). Energy use is a reoccurring subject in both regulations and research but is not the only aspect to consider if sustainability is to be reached (Ma, Cooper, Daly, & Ledo, 2012). Earlier research has shown a theoretical opportunity for the existing building stock to improve in both energy use and environmental performance. Further research is, however, needed to assess if building owners use the opportunity to improve the existing building stock and support sustainable renovations. More research was found to be needed where case studies of renovation measure have been carried out on buildings. The question is if building owners work in a systematic way including all sustainability aspects and how they use the information, methods and tools that are available to assure sustainable renovation.

1.3 Hypothesis

Due to the de facto research gap, presented above, the hypothesis put forward in this thesis is as follows: Building owners do not, in a systematic way, take into account and manage sustainability aspects in pre-renovation decisions.

1.4 Aim and research questions

The aim of this study is to examine the hypothesis by investigating the following research questions:

1. Can sustainability aspects be implemented before making a decision to renovate?
2. Are sustainability aspects considered before making a decision to renovate?
3. How have the sustainability aspects of profitability, energy and indoor environmental quality been implemented in the renovations?
4. How can sustainability aspects of climate change potential be implemented in the assessment of energy efficiency renovation measures?

1.5 Limitations

The studies presented in this thesis originated from the perspective of building owners and their renovation projects. The aspects included in the appended papers are examples of sustainability aspects that are relevant in a renovation project. In the first four studies, Papers I-IV, the aspects investigated were looked at from a broad perspective from that for the building owners when considering renovation projects. In Papers V-VII the focus was narrowed down to only look at the environmental category of climate change potential. This part of the study was therefore more in-depth although it did not include any additional categories, such as economic or social aspects.

This study mainly focuses on the renovation of multifamily buildings with the exception in one of the sub-studies in which a school building was used for a case study. These two building types constitute a large part of the building stock with renovation needs in Sweden.

1.6 Outline of the study

In this thesis, seven studies are presented. In Chapter 1, the overall research area relevant to the studies is presented. The different methods of investigating and collecting data in the appended publications to this thesis are further described in Chapter 2. Each method is briefly explained and a description is given of how it was implemented in the different studies. The contributions of each of the different studies towards answering the research questions are presented in Chapter 3. In Chapter 4, the hypothesis is discussed based on the results from the studies. Further conclusions from the study can be found in Chapter 5.

To answer the research questions, seven studies were carried out and these are presented in full in the appended papers. The research questions dealt with by each Paper are shown in Figure 2.

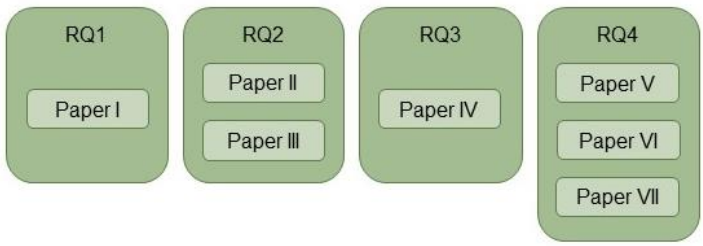

Figure 2: The research questions (RQs) and the corresponding appended Papers.

The first study was a literature review of published research about renovation and this was presented in Paper I. The review formed the basis for an assessment of the status of the research that had been carried out with a focus on renovation measures.

To learn from earlier experiences of renovations, specific renovation projects were selected for analysis. For each of these projects, relevant documentation about the renovations was gathered. How profitability was taken into consideration in the decision process before a renovation was analysed in Paper II. The study was conducted by analysing the documentation from six renovation projects as case studies. In Paper III, eight renovation projects as case studies were analysed to assess how energy and indoor climate aspects had been included in the pre-renovation decisions. Here, energy and indoor climate information was gathered from documents, questionnaires and interviews.

The studies presented in Papers II and III analysed specific sustainability aspects in the decision phase of a renovation. To further investigate what aspects had been discussed and their impacts on a renovation decision, one case study was analysed by action research and an account is given in Paper IV.

To assess the climate change potential of implementing energy efficiency renovation measures, computer simulations were used to perform sensitivity analyses (uncertainty analyses and parametric analyses). The choice of method to assess the climate change potential was determined by testing different tools for conducting life cycle assessments (Paper V). The climate change potential of five energy efficiency renovation measures were assessed, taking into account the uncertainties in the life cycle inventory data (Papers VI-VII).

2 Methodology

To carry out the work in this thesis, hypothetico-deductive driven research was conducted. A hypothesis was formulated with the objective of proving or disproving whether sustainable aspects were systematically considered and managed when making the pre-renovation decisions before carrying out a renovation.

The studies presented in this thesis were mainly carried out as qualitative case studies in combination with different data collection and performance methods. The different methods are shown in Figure 3.

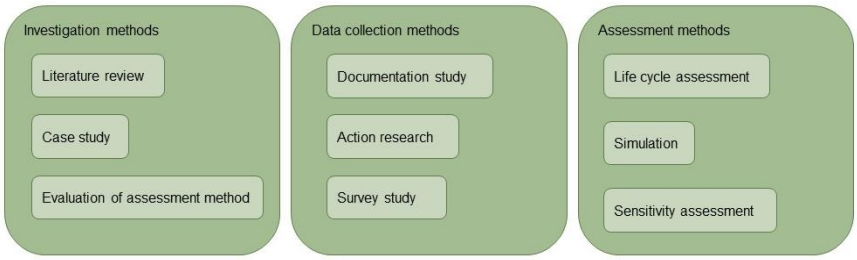

Figure 3: Investigation methods, data collection methods and assessment methods used in the study.

The methods that were used in the different studies are illustrated in Figure 4.

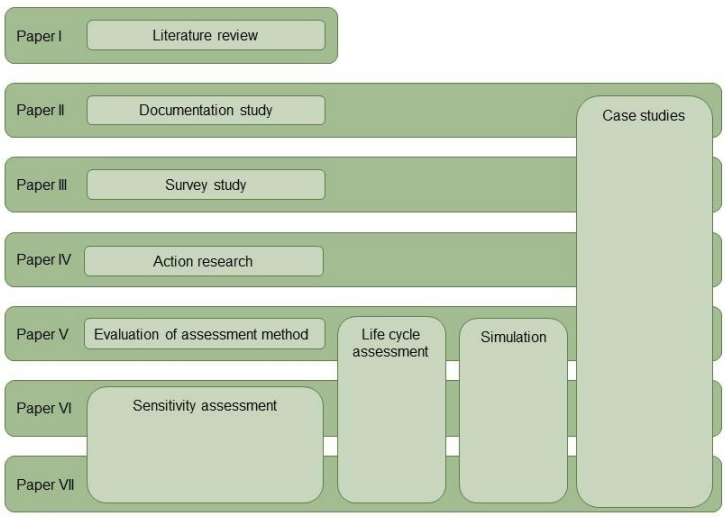

Figure 4: The different methods used in the Papers.

2.1 Investigation methods

For each of the studies, a suitable investigation method was chosen to ensure that the aim of the study could be fulfilled. In the literature review, the aim was to investigate previously performed research that had been relevant to the subject. In the studies in which different cases were used, the aim was to analyse a specific example, such as a renovation project or a renovation measure, and apply the findings to the building stock in general.

2.1.1 Literature review

In the literature review, the state of the art of a given subject was established (Säfsten & Gustavsson, 2020). This made it possible to relate an ongoing study to earlier research and to build on previously established knowledge.

A literature review was carried out to establish the state of the art for research on renovation (Paper I). Two scientific databases were selected to search for relevant references to article in journals, conference proceedings and reports. The databases, ScienceDirect and Scopus were chosen after carrying out a test search in several different databases. Scopes and Science Direct gave the most relevant results in this search and were chosen for the more detailed search.

The subsequent search was performed using specific search phrases to increase the relevance of the results. Both truncations and Boolean operators were used for the search phrases. Titles, abstracts and keywords were searched to avoid references in which the search phrases only occurred on single occasions. The study was limited to publications in English and Swedish.

The relevance of the results was based on the contents of each reference being within the study´s boundaries, which were:

- Renovation
- Multifamily buildings
- Temperate climate
- Present-day technical relevance

The climate boundary was not based on the geographical origin of the article or report but on the relevance of the contents to temperate climate. Studies were included if they were deemed to be relevant and adaptable to multifamily buildings even if they had not specifically been carried out for this purpose.

The categorization of the references was developed during the search so that the study could be adapted to the material found. In all assessments, the human factor is always present and, as this study was made in a collaboration between four

authors, the assessments were carefully discussed among the authors during the work although small variations could occur in the conclusions regarding relevance and categorization. The references were analysed from three perspectives: status determinations, renovation strategies and renovation measures. In this study, the term 'strategies' was used as a collective term for different approaches, such as methods and tools.

There are a great number of possible ways and choices to make when carrying out a literature review. This study could have been expanded, for example, to include searches in more databases, an increased number of search phrases or a broader scope of the study. More databases were not included as the test searches were not regarded as being able to show any added value. In all the search phrases, the words 'refurbish', 'retrofit' and all inflections of the word 'renovation' were included. This meant that any study that could have been implemented in a renovation, but did not include any of the words used in the search phrase, was not included in this study. Adding more search phrases might have added to the study but would have also resulted in a greater number of irrelevant references. If the scope of the study had been wider, the study would have had a complexity that could have reduced the relevance of the results. The boundaries were set in order to focus on the results that were aimed for, as well as making the search feasible to perform.

2.1.2 Case studies as data sources

A case study can be used as part of a methodology by using a sample of relevant subjects to conduct assessments and analyses with the aim of generalising a broader conclusion (Säfsten & Gustavsson, 2020). In the studies that were conducted for this thesis, several case studies were used. The case studies were either renovation that had been carried out for whole buildings or for individual renovation measures. General information about the case studies was analysed or used as input data in the analyses.

Different methods of collecting data in a case study can be used. One way is to collect data from previously published documents, which is called performing a documentation study (Säfsten & Gustavsson, 2020). Information from the case studies presented in this thesis was gathered from several different sources, such as published documents, interviews and questionnaires, and through action research by following the activities in the project by participating in regular meetings.

How profitability was considered before deciding on a renovation project was analysed in six renovation projects carried out as case studies (Paper II). The information was gathered by carrying out a documentation study.

With the aim of analysing how the sustainability aspects of energy use and indoor environmental quality were included in decisions before a renovation was carried

out, a case study survey, which included questionnaires and interviews, was carried out on eight previously completed renovations (Paper III) (Farsäter, Strandberg, & Wahlström, 2019).

One of the case studies was subject to an ongoing evaluation, with the aim of taking part in and describing the process of the initial phase of the renovation of a school building (Farsäter & Olander, 2019). Data for the case study was collected by carrying out action research, described in more detail in Sub-section 2.2.2.

An analysis of different LCA tools was carried out in Paper V, by using information from a renovation measure that had been carried out. The aim was to use the same set of input parameters in the different LCA tools. An LCA for the case study was performed in all four tools. The four tools were evaluated for their usability. Depending on the required input data and limitations of the tools, the input parameters could also differ. Some generic data valid for the construction sector was available in the applied tools. In this study, the generic data was used to evaluate the adaptations or simplifications made in the tools.

The climate change potential was assessed by using five energy efficiency renovation measures as case studies in Papers VI and VII (Farsäter et al., 2021). The first four measures concerned the building envelope involved adding extra insulation in the attic, replacing the exterior panel walls, replacing windows with windows with lower thermal transmittances (U-values) and replacing the balcony doors with doors with lower U-values. The fifth measure was the ventilation measure, which entailed adding a supply duct system and an air handing unit with heat recovery to an existing exhaust ventilation system.

2.1.3 Evaluation of life cycle assessment tools

The comparison of the three LCA tools that had been specifically developed for use in the construction and real estate sectors, with a fourth tool that was a general LCA tool, revealed several significant differences. These are presented in Paper V. In the general LCA tool, OpenLCA, the data used for potential environmental impact can be accessed from different sources (GreenDelta GmbH, 2014) such as EcoInvent, GaBi or the JRC European Commission databases. The simplified LCA tools developed for use in the construction and real estate sectors included some input data on environmental impacts. In Beceren, this information can be accessed by visualising hidden tabs in the Excel-based tool (Olsson et al., 2016). In RenoBuild, the CO2-equivalent emissions for the district heating and primary energy factors (PEFs) are linked to an external source in the tool and can be changed if necessary (Mjörnell et al., 2014). The potential environmental impact of the amounts of materials and transportation distances were set as default values in the RenoBuild tool but these are not visible to the user. In BM, approximately 120 environmental product declarations (EPDs) are linked to the tool, with data on the potential

environmental impacts of different materials (Erlandsson, 2018). The environmental impact of some services can also be added to the tool, such as the impact of construction work. All materials have a default value for climate impact with the transportation of materials based on average values, depending on their weight and distance carried from their production facilities in Sweden. This default value can be changed by the user of the tool. The user can also import their own materials and services either by stating the potential environmental impact or by importing an EPD.

2.2 Data collection method

Different methods were used to collect data for the different studies presented in the appended publications and were chosen depending on the availability of data as well as on the aim of each of the studies.

2.2.1 Documentation study

A documentation study was be conducted to learn lessons from previously published information (Säfsten & Gustavsson, 2020). This is one way of collecting data, which, in this case, would be regarded as secondary data. Secondary data is suitable to use either to complement primary data or if the research is to study how someone else interpreted a situation or event.

Gathering data from documentation was the method used in Paper II (A synthesis of studies on renovation profitability). It was carried out by compiling published information about profitability evaluations in six renovation projects that were found to be relevant. These projects included renovations that had been carried out in multifamily buildings in Sweden. The aspect of profitability in the different projects was analysed by comparing the calculation methods and input data used in the projects.

2.2.2 Action research

Action research is a method that is used when a study aims to identify and solve problems by setting up collaborations between academia and practicians (Säfsten & Gustavsson, 2020). Action research can be carried out with different types of partners, either as directly involved partners or as observers.

The action research method was used, as observers, for a school building with the aim of obtaining a deeper understanding of sustainable aspects in the decision process sbefore carrying out a renovation (Farsäter & Olander, 2019). The

information for the analysis was obtained by following the project during a number of meetings as well as, on some occasions, contributing with comments during the process (Ahnberg, Lundgren, Messing, & Lundgren, 2010). The meetings were held with decision-makers from the public school system and the owners of the school building (a municipally owned company) taking part. The meetings were documented, the subjects discussed were identified and analysed, and then divided into the sustainability categories of environment, economic and social issues.

2.2.3 Survey study

A survey study can be used to determine the presence, scope and relationship between different variables (Säfsten & Gustavsson, 2020). The study can have a descriptive purpose and answer questions about what, who, when or where, or have an explanatory purpose and answer the questions of how and why. The use of a questionnaire is a common method of collecting data in a survey study. Another way of collecting data is by using interviews.

Questionnaires and interviews were carried out among representatives of building owners that had completed a renovation of a multifamily building and these are discussed in Paper III. Renovation projects that were relevant to the study were those that had been completed and had included energy efficiency measures.

In the renovation projects, contact persons were identified and approached about participating in the study. After agreeing to participate in the study, a questionnaire was sent out. A total of eight project representatives answered the questionnaire either in writing or by telephone interviews. In some of the projects more than one person had to be involved to provide answers due to the scope of the questions and roles of the different participants in the project. Three of the eight renovation projects that were analysed in this study were part of the BeBo *Rekorderlig Renovering* project. BeBo is a Swedish network of building owners and is financed by the Swedish Energy Agency (BeBo, 2020). The additional five projects were found through contacts in the SIRen research environment.

The parameters that were studied were selected from previous studies and literature within the research area. Focus, regarding the parameters, was on input data for building physics properties and indoor environment factors for energy efficiency evaluations and follow-ups. Specific focus was placed on parameters that were of relevance to building owners.

In addition, two in-depth interviews were held with professionals who had been involved as consultants in many renovation projects in Sweden. Furthermore, the study ascertained whether a follow-up of the project had been carried out and whether experiences gained from the renovations had been assembled.

2.3 Assessment methods

2.3.1 Life cycle assessment

Life cycle assessments (LCAs) are standardised methods to assess the potential environmental impact of different processes and services, including those in the construction and real estate sectors. The methods identify all emissions that are released into the air, water and land due to the processes connected to a product or service during its whole life cycle, from raw material extraction to their end-of-life treatment. The impacts on the environment of the different emissions are identified and compiled in different environmental impact categories. The impact that different products have, for example, on the amount of natural resources required, land use, light and noise pollutants, can also be assessed in an LCA. Two of the most common and more developed environmental categories are global warming potential. In these categories, the amounts of greenhouse gas emissions and the potential that the emissions have to impact on air and water temperatures are calculated.

LCA Standard

Overall guidance on how to carry out an LCA is provided in the standard SS-EN 15643:2021 but it leaves a high level of adaptability and flexibility when carrying out an LCA (Dossche, Boel, & De Corte, 2017). There are no specifications of tools, databases, functional units, or the life cycle stages that should be used. The standard states the need for a high level of transparency in all LCAs as this is essential to be able to assess and compare results. In addition to the overall standard requirements, SS-EN 15978:2011 also describes the adaptation of LCAs for use in the building sector (SS-EN 15978). The building process is divided into four life cycle stages: the A stage covers the manufacture of the building materials (modules A1–A3), their transportation to the building site (module A4) and the construction of the building (module A5); B, the use stage (modules B1–B7); C, the end-of-life-cycle stage (modules C1–C4) and D stage, the optional benefits and loads beyond the system boundaries.

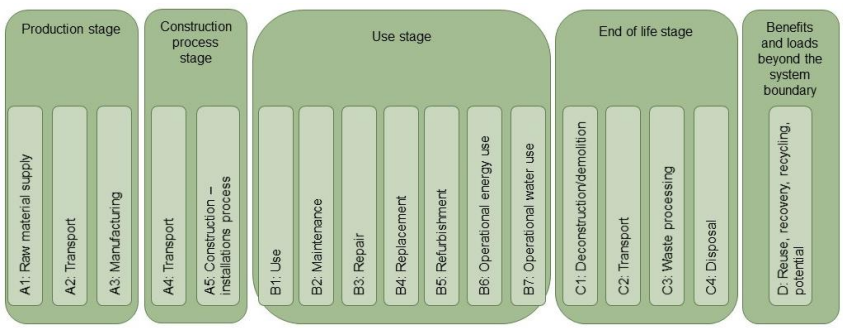

Figure 5: Life cycle stages for a building according to SS-EN 15978.

Environmental product declaration, EPD

An environmental product declaration (EPD) is a standardised presentation of the results from an LCA. The environmental impact of a product or service, and how it is presented in an EPD, is regulated in the EN 15804:2012+A2:2019 standard. This standard stipulates what information that must be presented in the EPD as well as in which life cycle stages, and how the environmental impact categories should be calculated. For example, how biogenic carbon should be treated when calculating its global warming potential. An EPD can be registered and published in a database, if it fulfils the requirements of the database and is validated by a third-party organisation (EPD type III). It is common for manufacturers to have initiated the LCA presented in EPDs.

Life cycle inventory data, LCI

All emissions that are released during the different life cycle stages of a product or service are needed as input data when performing an LCA. This data is called life cycle inventory (LCI) data. There are two different kinds of LCI data, namely generic data and manufacturer´s specific data (Swedish Institute for Standards, 2012). The data in different LCA software and tools is often generic data. Generic data can also be found in separate LCI databases. Generic data can be either average data for a specific product or service for a certain region or a specific product group. The generic data can also be based on manufacturer´s specific data. Manufacturers´ specific is data from the manufacturer for a particular product.

Functional unit, FU

When carrying out an LCA, the way in which the results are presented is determined by the functional unit of the study. In an EPD, the functional unit that the results from an LCA should be presented in is specified in the product category rules (PCR) document, if there is a PCR for the product or service. Depending on the functional unit, comparisons of different LCAs can become difficult. In this study, all results are presented in kg CO_2-equivalants per square meter of heated floor area of a renovated building that fulfils the Swedish building regulations. In the new regulations for climate declarations in the Swedish building code, the results should be presented in kg CO_2-equivalants per gross floor area of a building.

The functional unit of the materials included in a study affects how the study is conducted as well as its results. Depending on the type of calculation carried out on an amount of a certain material, some assumptions are necessary to be performed. For example, for a particular insulation material, the units used in an EPD for the material are often expressed as an environmental impact per square meter of material with an R-value of 1. The thickness of the material and its heat conductivity also needs to be known. In some databases, the impacts of an insulation material

might be expressed per kilogram of material. In this case, the density of the material will influence the calculation. Since the density does not have a linear relation with the heat conductivity, the results can differ, depending on the assumptions made in the study.

Environmental impact category

Different environmental impact categories can be assessed in an LCA. The most common category that is assessed is global warming potential. This category assesses how greenhouse gas emissions affect the climate and assessments can be carried out including or excluding biogenic carbon.

In the LCAs in the appended papers, the biogenic carbon has not been included. According to the Swedish regulations, biogenic carbon should not be included for either the material or for the sources of energy (The Swedish National Board of Housing, Building and Planning, 2018). If the biogenic carbon were included, the uptake of carbon would be seen as a negative value regarding the climate change potential and if the uptake were larger than the emissions, the total climate change potential of a material could also result in a negative value (Swedish Institute for Standards, 2012). This would mean, in an LCA, that the climate change potential would be lower the more a particular material was used.

According to EN 15804:2012+A2:2019, EPDs for biogenic carbon in construction materials should be declared separately. This applies to both the declared material itself and its required packaging. With the exception of when the biogenic carbon content is less 5 % of the material or packaging, the declaration of biogenic carbon can be omitted. Since the biogenic carbon is relevant during a specific life cycle stage or stages, materials that contain biogenic carbon must include modules A1-A3, C1-C4 and D in the EPD (Swedish Institute for Standards, 2012). Materials in which biogenic carbon is not relevant are not required to include all life cycle stages in an EPD.

Adaptation of an LCA

The LCA method was used in three different studies, presented in Papers V-VII, in this thesis. In all three studies, individual energy efficiency renovation measures were used as case studies. In the first study, different LCA tools were evaluated (Paper V) (Farsäter, 2019). One of the energy renovation measures was assessed in four different LCA tools using four different databases for the life cycle inventory data, either included in the tool or linked to the tool. Three simplified tools, specially developed to perform LCAs for renovation measures (BM, Beceren, RenoBuild), were compared to a fourth tool that is a general LCA tool with a European database link (OpenLCA with ELCD database). The tools were evaluated based on their advantages and limitations in performing the assessment.

In the following two studies, LCAs were carried out individually for five different energy renovation measures (Farsäter et al., 2021) (Papers VI-VII). The assessments were made using the OpenLCA software with the free European Life Cycle Database of the Joint Research Center version 3.2 (ELCD). The LCA included the production modules A1-A3 for the materials needed for the energy renovation measures and the operational energy stage B6 reduction that the measure had the potential to achieve for the building. The functional unit of the study is 1 m^2 heated floor area of a renovated building that fulfils the Swedish building regulations. It is assumed that the renovation measures carried out will prolong the building's life span by approximately 20 years. A calculation period of 20 years was used in this study (2020-2040). After this period, new decisions regarding further measures will have to be assessed. The lifespans of the components used for the renovation work were assessed using the methodology described in ISO 15686-2:2012 and ISO 15686-8:2008. Different sources were used for different components and each source was evaluated regarding its relevance for the analysis as well as for each case study. In the case of the building envelope measures, the added materials for the attic insulation, doors, windows and wall replacements all had expected lifespans of 30 years as assumed in EN 15459:2007. In this study, the lifespans of the newly installed air handling unit (AHU) and the existing ducts are assumed to be 20 years from that of the renovation (Dodd, Cordella, Traverso, & Donatello, 2017). The new duct system is assumed to have a life span of 30 years (ASHRAE, 2013) and supply air devices are assumed to have a lifespan of 25 years, according to the manufacturer (Klimatbyrån, 2015).

2.3.2 Simulations

A simulation, as the name implies, is a way of imitating reality and can be used to predict the results of a future situation (Säfsten & Gustavsson, 2020). Using simulations as part of the methodology of a study provides an opportunity to assess a situation that could be limited or even impossible to create in a laboratory or to measure in a real situation.

In this study, the climate change potential was simulated in an LCA tool. To measure or calculate, as an alternative to simulating, would be time-consuming. Measuring would take as long as the calculation period, for example 20 years, and would need to be performed and divided up for each stage of the process. Performing calculations would be possible but time-consuming if the uncertainties of variations in the input data were to be taken into account. The LCA method requires a life cycle perspective, which would be difficult to achieve by any other means than simulations.

2.3.3 Sensitivity assessment

Assessing how variations of different parameters influence each other can be carried out by performing a sensitivity analysis (Morgan, Henrion, & Small, 1998). A sensitivity analysis can be carried out using parameter studies or regression studies (uncertainty studies) (Groen et al., 2017). In a parameter study, the input value of one parameter is varied by setting alternative values and carrying out a single assessment for each chosen input value. In a regression study, one main minimum and one main maximum value are set for each parameter as well as a distribution between these values.

Two of the studies (presented in Papers VI and VII) included sensitivity analyses of the life cycle inventory (LCI) data, used in the LCA. The uncertainties were assessed according to the Ecoinvent data quality system for all sources of energy and materials that were included in the studies (Ciroth, Muller, Weidema, & Lesage, 2016). The quality system considered five different parameters of the LCI data: reliability, completeness, temporal correlation, geographical correlation and further technological correlation. Each parameter was judged at five different levels. Level 1 corresponded to the data being well represented in the analysed case and level 5 to where it was poorly represented. The uncertainty of each source of input data was judged according to the different parts of the matrix and how representative the data was for each analysed case. Each level of each parameter corresponded to an uncertainty factor. From the uncertainty factors, the geometric standard deviation was calculated according to the Ecoinvent data quality system. The distribution was set as a logarithmic normal distribution. This distribution was used as it is often found to provide a good representation of physical quantities that are constrained to being non-negative and are positively skewed, such as pollutant concentrations (Morgan et al., 1998). Lognormal distribution is particularly appropriate for representing large uncertainties that are expressed on a multiplicative or order-of-magnitude basis. The sensitivity analysis was performed using Monte Carlo simulations, more details about how the uncertainties of the different materials were assessed and the settings that were chosen for the simulations are presented in Paper VI.

The results are shown in boxplots and analysed with the aim of comparing the climate change potential for the additional energy use in the building with the climate change potential of the added materials. The additional energy use represents the climate change potential if the renovation was not carried out. The climate change potential of the added materials constitutes if the renovation was carried out.

Scenario assessment

In addition to the uncertainty analysis of the LCI input data for the source of energy and materials, a scenario assessment for the energy mix was also included in the study. The first energy mix scenario assumed that the sources of energy would

remain the same as they are today. This scenario gave the worst climate change potential. Additional scenarios were included in the study and these were based on two assumptions. The first one assumed that there would be no fossil fuels in the energy mix for heating by 2050, a similar scenario to that assumed by the Swedish Energy Agency (Energimyndigheten, 2016). This would lead to an increase in heating provided by electricity and biofuels but with an unchanged use of waste incineration and allocated sources. The second one assumed that the European electricity mix would tend towards today's emission levels of the Swedish electricity mix. The European electricity mix was, in the simulations, replaced by the Swedish electricity mix by 2040. A 'best case scenario' was also included, in which the electricity use attained the level of the present-day Swedish electricity mix.

Parametric study

In this study (Paper VII), a parametric study was made in addition to the uncertainty analysis. The parametric study was carried out in two parts. In the first part, different options for material use were assessed without comparing them to the energy use of the building. A minimum and a maximum climate change potential of the different options for materials were established in this way. In the second part, the option that showed the minimum and maximum climate change potential from the first part were assessed for climate change potential while also taking into account the uncertainties of the LCI input data. The climate change potentials of the materials were compared to the energy reductions for each measure with different scenarios for the energy mixes in the district heating systems. The assessments from the second part formed the basis for the decisions on whether or not to carry out the energy renovation measures.

3 Results

In the following sub-sections, the results from the appended papers that forms answers to the research questions are summarised. Additional results from each individual study can be found in the papers.

3.1 Implementation of sustainability aspects before deciding on renovation measures

Previous research shows that different strategies have been developed that can be used to consider sustainability aspects in the planning phase of a renovation (Paper I). In 87 references that were analysed, 81 different strategies were identified. The strategies were aimed at different players involved in the renovation projects and at different phases during the renovations. Approximately 60 % of the strategies were aimed to be implemented in the planning phase of a renovation and 38 % of those aimed to be used in the planning phase targeted building owners.

The different strategies covered the three main categories of sustainability – environmental, economic and social aspects – to different extents, as illustrated in Figure 6 from Paper I. The nine strategies that included aspects from all three of the main sustainability categories were also the strategies that included both social and economic aspects. Of the nine strategies that included aspects from all three categories, eight of them had been developed for building owners, to be used during the planning phase of a renovation.

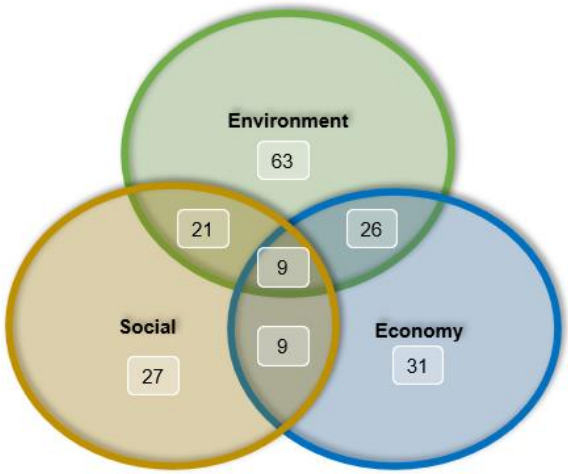

Figure 6: Distribution of types of aspects covered in the 81 renovation strategies.

The strategies that had been developed for single aspects were more detailed than those that included several aspects (Hamid et al., 2018).

3.2 Earlier experiences – taking into account sustainability aspects in renovation projects

Several earlier projects included sustainable aspects, as presented in the literature review in Paper I (Hamid et al., 2018). It is however not evident in the review whether the different strategies were implemented in any other renovation projects than the specific case studies that were used during the development or evaluation of the strategies. To investigate whether and how sustainable aspects had been considered, two new studies were carried out. The first study synthesised how seven renovation projects had considered the economical perspective of profitability (Paper II). By analysing documentation from these projects, it was possible to investigate how profitability had been considered. The second study compared and compiled how energy use and indoor environmental quality in the buildings had been taken into account in an early phase of eight renovation projects (Paper III).

3.2.1 Profitability

How profitability was taken into account in the pre-renovation decisions was analysed in a documentation study, presented in Paper II. Six renovation projects were used as case studies. In all six, the different building owners had defined what

was considered profitable, though there were differences in their 'perspective'. Three of the projects had carried out calculations from the perspective of both the company and the community, while the other three projects only included the company's perspective. In all of the projects, the calculations to evaluate their profitability included some kind of comparison between future cash flows and costs of the investments. The study showed some clear differences when calculating profitability but most evident were the differences in input values for the calculations. Due to slight differences in the calculation methods, the required input data varied. The calculation periods were only expressed in six of the calculations and these varied between 10 and 50 years. Another clear distinction between the projects concerned the costs included in the profitability calculations. The different types of costs are presented in Table 1.

Table 1: Types of costs included in the profitability calculations.

Costs	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Investment cost for maintenance	X	X	X		X	X
Investment cost for energy measures	X	X	X	X	X	X
Investment costs for improvements and raise the standard of the building	X	X	X		X	X
Operational (energy etc.)				X	X	X
Maintenance					X	
Re-investment					X	

The predicted profitability of a renovation project is highly dependent on the calculation methods used and their input data. To be able to learn from previous renovations, this information needs to be documented and presented clearly and transparently.

3.2.2 Energy and indoor environmental quality

Using questionnaires and interviews, it was investigated whether and how the energy uses and indoor environmental quality in the buildings had been considered in an early phase in eight renovation projects (Paper III). The study aimed to determine what information and data had been specified in the initial phases of the projects and how this information had been obtained.

The analysis included different parameters for each building's energy use, building physics properties and indoor environment. How these additional aspects were considered or not in the case studies is shown in Figure 7.

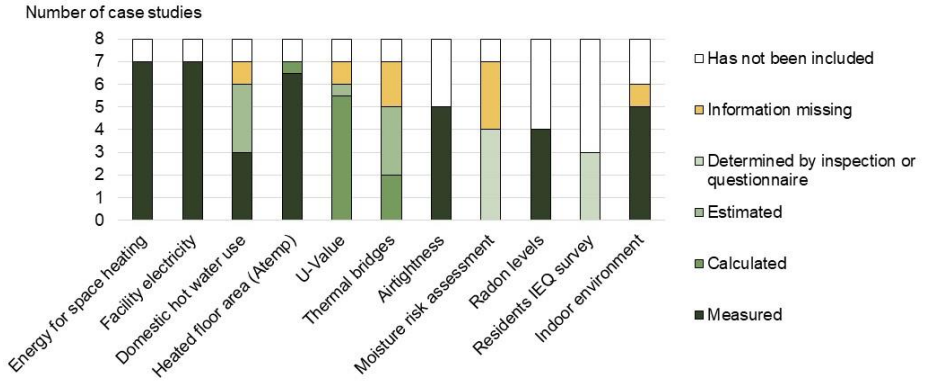

Figure 7: Sources of information for energy use, building properties and indoor environmental aspects were gathered for the eight case studies. IEQ stands for indoor environmental quality.

It is evident in Figure 7 that some parameters were treated in similar ways in the different case studies:

- The energy needs for space heating and facility electricity, in most cases, were included by measuring how much they were used.
- The heated floor area was, in most cases, measured.
- In the four cases in which radon levels were included in the pre-renovation decision, they were always measured. The study also showed that in the cases in which radon had not been taken into account, the reason was that it was considered irrelevant, either due to the geographical location of the building or previous measurements, i.e. even when the parameter was excluded it was done for similar reasons.

The analysis revealed differences between the renovation projects regarding what information had been gathered and how. For example:

- In seven of the eight projects, measurements were carried out to establish the energy use for heating and facility electricity but only three of the projects measured the domestic hot water use to establish its energy need. In the other cases, the usage was estimated in three of them, not included in one of them and, in the last project, there was no indication as to whether it had been included or not.
- In four of the eight projects, moisture risk assessments were conducted prior to renovation but only one project followed up with an assessment after renovation. Two of the respondents in this study emphasized the

importance of moisture risk assessments being performed in renovation projects.
- As part of the BeBo *Rekorderlig Renovering* strategies, the renovation projects were required to carry out airtightness tests on the buildings. The three projects in this study that followed the BeBo strategies carried out the test. In addition to the BeBo projects, two more of the eight projects had included an airtightness test.

Further results from the study can be found in Paper III. One conclusion from the study was that even after analysing the questionnaires and interviews there were still uncertainties regarding the gathering of information before carrying out a renovation. The study encountered numerous obstacles regarding the collection of information. In Paper III it was concluded that useful information about renovation projects seemed to have been known only by certain individuals and was not systematically documented for future use.

3.3 Sustainability aspects in the pre-renovation phase

In Paper IV, a study is presented in which the discussions in the initial phase of a renovation of a school building were followed. The different aspects that were discussed were documented in the study and classified within the concept of sustainability. The aspects that were discussed between the representatives from the municipal school board and the building owners were:

- Technical status of the building
- Number of children/demography
- Indoor environment
- Building accessibility
- Alternative location during construction
- Time schedules
- Function of the school building
- Energy use
- Costs
- Architectural and cultural values

Most of the aspects discussed in the pre-renovation decision concerned social sustainability aspects that had a direct effect on the users of the buildings. The only non-social aspects that were discussed were energy use and costs of investments.

The aspects were mainly discussed based on the experiences of the people attending the meetings. The additional analyses that were carried out were a technical status

assessment, including an assessment of the building's accessibility (external consultant), and a demographic analysis carried out by the municipality.

A discussion in Paper IV concerned the architect's involvement in the project. In the later part of the initial planning phase for the renovation, the architect was introduced to the project. The architect was brought in to develop a proposal for the school based on the issues that had been discussed. This was a process in which a rough initial proposal was produced and from which four more versions were developed. In addition to the aspects that had already been discussed for the school, the architect was asked to consider its architectural and cultural values. The process of including these aspects was initiated after the first rough proposal had been developed. Without any further evaluation than the information supplied by the building owners, the first rough proposal was developed further. After an initial cultural value evaluation, changes were made to the proposal, and it was also decided to carry out an evaluation by an antiquarian. After the antiquarian´s evaluation, the proposal was again developed to form the final extensive renovation plans (third renovation option). It was discussed in Paper IV how the project might have been affected if the antiquarian evaluation had been carried out earlier. Some of the measures discussed for the school building would have then been rejected at an earlier phase. This would have led to the discussions being more efficient and the architect's work would also have been more efficient and concentrated.

3.4 Pre-renovation evaluation of climate change potential of energy efficiency measures

In the studies presented in Paper VI and Paper VII, assessment of the climate change potential was carried out for five energy efficiency measures. It was assessed if the buildings climate change potential impact would increase or decrease by carrying out the renovation measure or not. This was performed by comparing the climate change potential of the additional energy the building would use if the measure was not carried out, with the climate change potential of the added material that the measure would imply.

To be able to consider the climate change potential in a pre-renovation decision, the input data that is needed for the assessment needs to be known. In an early stage, the input data is usually uncertain. In the performed assessment consideration was taken to the uncertainty of the life cycle inventory (LCI) data for both the material use and the potential energy saving.

In Paper VI, the original material choices used in the case studies were calculated and the average Swedish district heating mix was used. In Paper VII, additional

material choices were assessed together with the district heating mix for the locations for the case studies.

3.4.1 Environmental impact from energy sources

In addition to the uncertainty of the LCI data, the potential environmental impacts of different energy mix scenarios were assessed. Three different mixes of energy sources of the district heating system were examined; the average energy mix in the Swedish district heating system, the energy mix for the city Lund and for the city Linköping. In the study, the energy mix of these systems are, in one energy mix scenario, assumed to stay the same during the whole calculation period of 20 years.

Furthermore, for each of the three district heating systems, additional future energy mix scenarios were included in the assessments, referred to as "Future" in the studies. The future energy mix scenarios were based on the assumptions that fossil-based fuels will not be used after 2050 and that the environmental impact of the electricity mix will be reduced. The electricity mix is assumed to go from the European electricity mix towards the average Swedish electricity mix. Over the 20 years of calculation period, the speed of the transformation of the electricity mix is assessed in three different scenarios. With the assumption that the transformation will occur equally over time, the average between the two different electricity mixes are used, which means that each of them are used for 10 years. This scenario is referred to as 10/10. A 'best case' scenario is assessed, where the Swedish electricity mix is used for the whole calculation period (0/20) and a step in-between is used where the European electricity mix is used for 5 years and the Swedish is used for 15. The different energy mix scenarios are further described in Paper VI and Paper VII.

In Figure 8, the climate change potential of the different mix of energy sources in the district heating systems are presented. The results show that the climate change potential for Linköping is higher than both the Swedish average district heating system and for Lund. This means that carrying out energy saving measures will decrease the climate change potential more if the measures are performed in Linköping than in Lund.

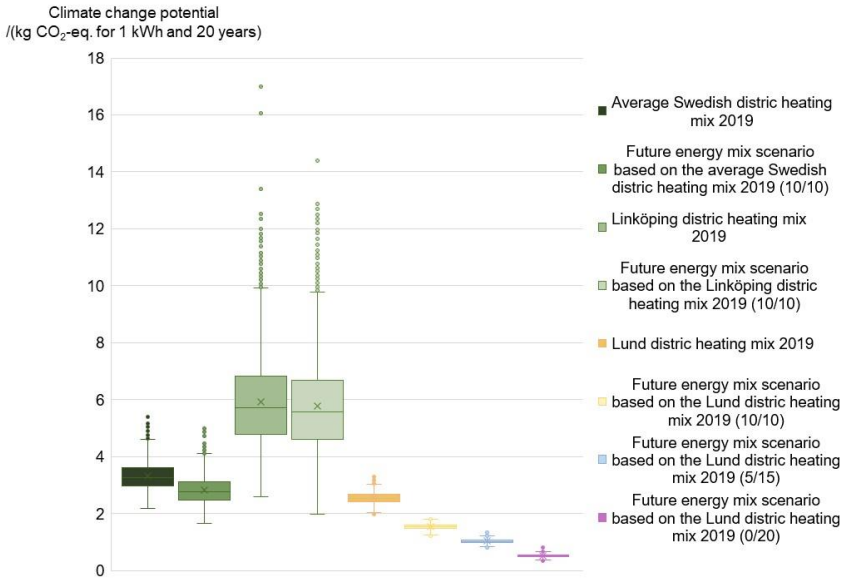

Figure 8: Climate change potential for the energy mix scenarios, per kWh over the 20 years of calculation period.

The energy mix for Lund resulted in the lowest climate change potential of the three different energy mixes that were assessed. The energy mix with the lowest decrease of climate change potential means that energy efficiency measure has a risk of not resulting in a decrease in climate change due to the added climate change from the materials. Two extra scenarios for the energy mix in Lund were included in the assessment. The scenarios were added as best-case scenarios to assess the risk of the renovation measure to not result in a decreased climate change potential for the renovation measure. The first best-case scenario is a theoretical energy scenario, in which the electricity mix was improved to the lowest level of emissions already today. However, this is not the case in reality, as the electricity grids in Europe are interconnected and the electricity mix used in 2020 do not have as low a climate change potential as the Swedish mix.

3.4.2 Environmental impact of material

In a parametric study additional sources of LCI data for materials were assessed. The additional sources of LCI data were gathered from EPDs of the relevant materials that were included in the assessments of the renovation measures. As an example, climate change potential of different sources of LCI data for windows found in EPDs is shown in Figure 9. The windows have different characteristics such as different U-values, different frame materials and are manufactured in different countries. Looking at the climate change potential for the windows, no

pattern on what characteristics that would indicate a high or low climate change potential can be identified. A pattern might be visual if the sample of data would be larger. From Figure 9 the minimum and maximum impact of climate change potential can be identified for further analysis.

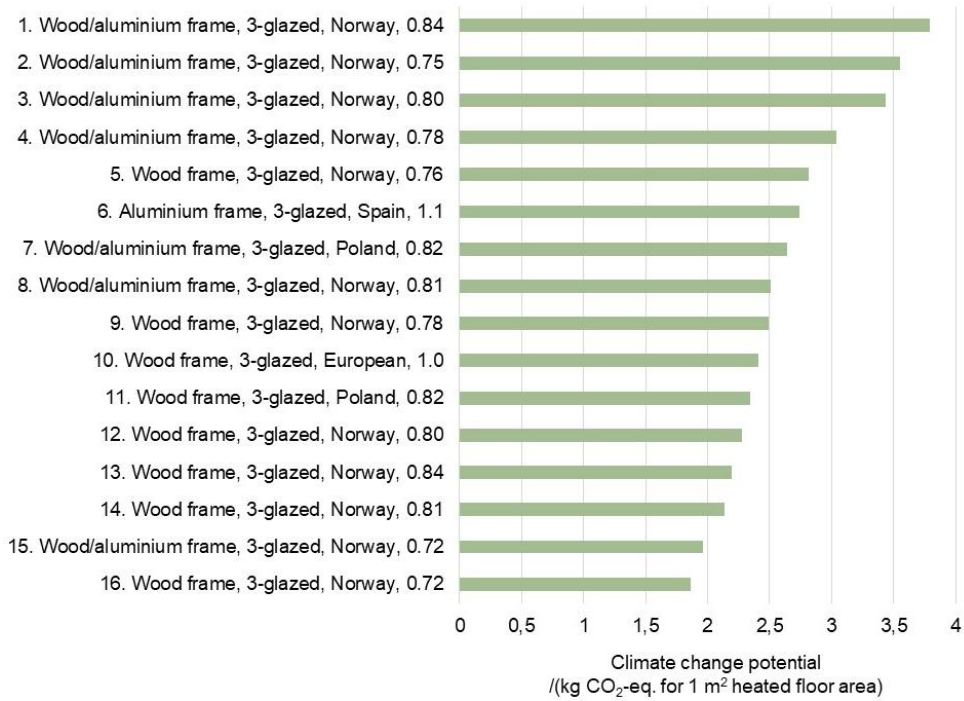

Figure 9: Climate change potential of different windows. The sources for the materials are given in Paper VII.

3.4.3 Environmental impact of renovation measure

Considering the source of energy in the Swedish energy mix, all five renovation measures resulted in a decrease of climate change potential if the renovation measures are carried out. Both with the assumption of a continuance use of the energy mix as it is today and with the assumption that the energy mix will increase renewable and eliminate fossil-based energy sources in the future.

The results for the different energy efficiency renovation measures varied when the energy mix scenarios for Lund and Linköping was considered. When comparing them with a 'best case scenario', only the window replacement measure did not overlap. An overlap arises when the uncertainties of climate impact of material production are at the same or higher level as the climate impact of the future energy

use. It is shown in Figure 10, that the material choices for the windows have a lower climate change potential than any of the energy mix scenarios.

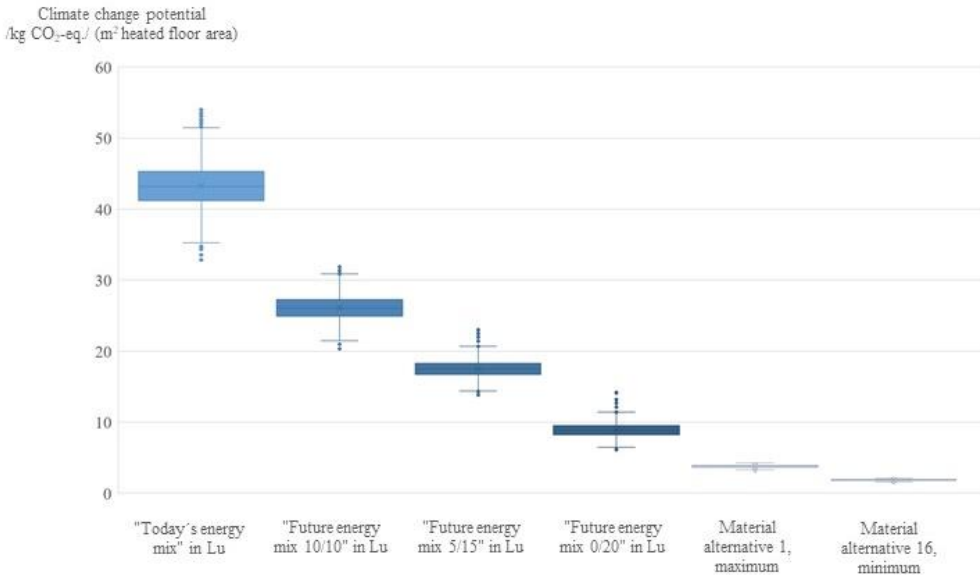

Figure 10: The Climate change potential for the exchange of the windows (minimum and maximum alternative) in comparison with the extra energy for the building if the measure is not carried out. Results are shown with consideration to the uncertainties in the input data and with four different scenarios for the energy mix in Lu.

Window replacements did not overlap with any of the energy mix scenarios and the ventilation measures only overlapped with the 'best case scenario'. These two measures are the ones with the largest energy saving potential. Adding insulation in an attic and wall replacement both had an overlap with the 'future energy mix 5/15' energy mix scenario and both measures had limited potential for saving energy. This indicated that the choice of material becomes more important when there is a lower potential energy saving for the renovation measure.

4 Discussion

In the literature review, it is evident that strategies for assessing sustainable aspects have been developed to be used in renovation projects. The most common target group for these strategies during the planning phase of a renovation were building owners. Whether these strategies had been used in real renovation projects was not evident in the literature review, except in the case studies that were used during the development or evaluation of a particular strategy. In the eight renovation projects that were analysed to investigate how input data had been obtained for a renovation, three of the projects had planned to follow the strategy that BeBo had been developing simultaneously with the projects (BeBo, 2016). In the case study concerning the school buildings project, the building owners did not, at that time, use any particular method. In order to make further progress when carrying out sustainable renovations, having an overview of the different strategies might increase the possibility of including a broader spectrum of sustainability aspects as well as considering each relevant aspect at a deeper level. As Paper I shows, there are strategies that can be used to support building owners in a renovation process. The issue does not seem to be a lack of strategies but rather the reluctance to implement and follow up of existing strategies to develop them further and to evaluate their effects.

In the questionnaires (Paper III) conducted among building owners, it could be seen that measurements were uncommon both in status assessments and in follow-ups. The measurements that were likely to have been carried out, both in the research and on behalf of the building owners, were temperature measurements and, on a few occasions, even measurements regarding some other indoor environmental issues, such as ventilation rates and relative humidity. The questionnaires (Paper III) show that building owners, in some cases, had performed indoor environmental surveys involving residents before a renovation had been carried out and a few had also carried out a survey afterwards. In the school case (Paper IV), measurements had been carried out in the buildings as part of a bachelor thesis in 2014. During the discussions in the initial phase of the renovation, measurements had not been discussed by the building owner or the municipality. Chu & Lindblom (2016) concluded that carrying out measurements in a renovation project is a profitable strategy compared to the cost of the potential additional energy needed due to uncertainties. There are several developed methods to better consider and document indoor environmental quality and energy use predictions of a building. An example

is the SQUARE quality assurance system that stipulates that indoor environment demands should be verified using measurements (Kovacs & Mjörnell, 2010). This is so that it can be evaluated whether the desired indoor environment has been achieved in the renovation.

This thesis includes two different studies in which previous renovations were analysed (Paper II and Paper III). In both of these, it was evident that information from earlier renovations was limited. It seems, in these cases, that there was a lack of systematic documentation about how the information before a renovation was generated. Information seems to have been missing or linked to an individual person. Return of experience is therefore vulnerable as people change jobs or retire. This also restricts the dissemination of information about previously gained experiences to those involved in future renovation projects. Johansson (2017) came to the same conclusion and lifts the risk that missing or incomplete information can lead to a higher cost for the renovation measure. The insufficiency of information in the initial phase of a renovation has also been concluded in other studies (Olsson et al., 2015; Thuvander et al., 2012). However, the earlier studies also found that there is a lack of tools, which do not seem to be the case, according to the results of the literature review performed in this thesis.

During the initial discussions concerning the school renovation (Paper IV), it was evident how important earlier experiences were in the process. How the discussions were carried out were, to a great extent, built on earlier experiences from other renovations that the participants had been involved in. Hastig & Tapper Jansson (2014) also concluded that the way in which a renovation project was carried out was dependent on the participants' earlier experiences. Among the parties involved in the school renovation (Paper IV) there were some that would have retired before the project was finished. The transfer of information to a newly involved participant is a crucial step for continuity and following up a project.

It can be seen in Papers II and III that there was no common ground for documenting experiences of renovations. Högdal (2013) also concluded that there was a need for a basic standard for documentation of renovations so that different projects could be compared. Due to the differences in methods and documentation, comparisons between different projects are difficult.

When assessing the climate change potential of an energy renovation measure, the assessment needs to be performed for each package of measures that is under consideration. Taking into account the mix of energy sources that is relevant to a specific case and making a realistic assumption about a future energy mix, as well as making a conscious decision about which materials to use, all influence the climate change potential of the energy efficiency measures.

In any study that is carried out, the sources of information need to be evaluated for their accuracy. A method to evaluate the reasonable validity of a source is, therefore, needed (Säfsten & Gustavsson, 2020). In an LCA, the main input data is the life

cycle inventory data. The assessments conducted in this study are results of the assumptions based on the materials that are available today, the energy mix used today, and the future energy mix based on the predictions and environmental goals in today's society. These circumstances will change over time and the importance of conducting detailed LCAs before implementing energy renovation measures will increase in the future.

Another input data in the performed LCA is the energy use of the building. In performing energy simulations, several sources of error are well known in energy simulations, such as user behaviour related parameters. To include variations of the energy use, a larger study would have to be carried out, and several other factors that influence a building's energy use taken into account.

The discussions presented in this chapter concern the hypothesis formulated for this thesis: Building owners do not, in a systematic way, consider and manage sustainability aspects when making pre-renovation decisions. This study has shown that there is a potential to manage and consider several aspects of sustainability in a pre-renovation decision. It also shows that this is, to some extent, performed in renovations that has been carried out. The management of sustainable aspects is not always performed in a systematic way and it is often a lack of documentation on what has been done. In few cases has the uncertainty of the information in this early stage been considered.

To make a more sustainable decision regarding a renovation, building owners need to have the information and knowledge to make relevant predictions regarding aspects of environment, economic and social. Common for all aspects, seems to be the need for building owners to adapt the aspect to the conditions of their company and the renovation project. The sustainable aspect of energy use is further developed to be treated in an early stage of a renovation then aspect such as climate change potential. When it comes to climate change potential and other environmental aspects, the research and development has increased in later years. In this study, several social aspects have been treated. There seems to be a variation of social aspects that are treated in different renovation projects depending on what is considered to be of importance.

To make a more sustainable decision with regard to a renovation, the whole process of the renovation, as well as the building's total life span, need to be considered. Building owners need to have the information and knowledge to make relevant predictions regarding a large number of environmental, economic and social aspects. As discussed in this thesis, the existing strategies do not seem to be used and the performed renovations in the case studies are not documented systematically. Even with the lack of information from renovation projects carried out, the pre-decisions on renovations seem to build on experiences from earlier renovations that have been carried out, but it is based in experiences from the included participants on an individual level. Within the research environment

SIRen, a framework has been developed those structures and compiles aspects to consider during a renovation process for different actors involved in the process (Wallentén & Mjörnell (2021).

When it comes to LCA, the use of uncertainty and scenario assessments is one approach to consider the lack of information in the initial phase of a renovation. The implementation of climate declaration in the Swedish building code has increased both the information on how to consider climate change potential and increased the access to LCI information for building materials. What the Swedish national board of housing, building and planning will conclude when it comes to the possibility of introducing climate declarations for building alterations, reconstructions and extensions awaits to be seen.

5 Conclusions

The hypothesis in this thesis has been investigated through four research questions. The following conclusions can be drawn:

- *Can sustainability aspects be implemented before making a decision to renovate?*

The literature review, Paper I, showed that there is a potential for implementing sustainability aspects in the pre-renovation decision. Several sustainability aspects were treated in the strategies developed for building owners to aid them in the decision-making process before a renovation. Nine of the strategies included aspects found in all the three sustainability categories, i.e. environmental, economic and social, and eight of these had been developed to be used by building owners in the pre-renovation phase.

- *Are sustainability aspects considered before making a decision to renovate?*

All the case studies in Papers II-IV implemented different sustainability aspects in their renovation processes. But the strategies that were found in the literature review had not been implemented in any of the case study renovation projects. Instead, it can be seen from the analysis of documents, questionnaires, interviews and ongoing evaluations that building owners rely heavily on the previous experiences of individuals as a basis for their decisions.

In the case study presented in Paper IV, issues to fulfil the needs of users during an early phase of a renovation project were discussed. The technical and accessibility status of the building as well as the time schedule, costs and, to a small extent, energy efficient measures were also discussed. In the later stages before the pre-renovation decisions, cultural aspects got a high priority in the discussions. However, none of the developed strategies, found in Paper I, where used in the case study in Paper IV.

- *How have the sustainability aspects of profitability, energy and indoor environmental quality been implemented in the renovations?*

The information regarding how profitability was assessed in the renovations shows that there were significant differences in both methodologies and the input data that were used. Whether the sustainability aspects, with regard to energy and indoor environmental quality in the renovation projects, were actually taken into account is unclear. The experiences from the studied cases show that there was a lack of documentation of the renovation processes and this complicated the evaluation of how sustainability aspects had been considered.

- *How can the sustainable aspects of climate change potential be implemented in the assessment of energy efficiency renovation measures?*

The assessments of the climate change potential have been possible to perform with the uncertain information that was available before the decision of a renovation. It is evident that in an initial life cycle assessments need to be carried out for the mix of energy sources and future energy mix scenarios specific for a geographical location.

The assessments need to be performed due to the uncertainty of the future energy mix. If the energy mix is assumed to change in the future, with less fossil fuel and more renewable sources for electricity, it will be important to conduct an assessment of any energy renovation measures.

Material choices can be carried out by assessing information presented in EPDs. The minimum and maximum variations in the climate change potential of materials show that assessments of different choices of materials should always be carried out before a renovation measure is decided on.

To summarise, the hypothesis in this thesis has been partly proven in the performed studies. In some areas of sustainability, building owners have started to manage and treat some aspects systematically but in some other areas it is less developed and need to be improved to achieve more sustainable renovations.

6 Future work

Further studies are needed to evaluate how sustainability aspects could be implemented in renovation projects. In order to benefit from the strategies that have been developed, further analysis of their implementation will be necessary. This also applies to the practicability of combining different detailed strategies with the aim of achieving more sustainable renovations.

In the goal to achieve sustainable renovation, more detailed studies on specific aspects and interdisciplinary studies on how to combine different aspects would be beneficial. Since the societal goals and aims develop, so need the research to continuously contribute to forming goals as well as how to implement and how to follow up if the goals have been met.

Further studies could carry out analyses on how the assessment of sustainable aspects are implemented and followed up during the different stages of a renovation project. This would supply additional information on what is needed before the pre-renovation decision to assess if a decision was the correct one or not.

Future studies on the possibility for a common ground of documenting renovation projects could enable the possibility to benefit from earlier performed renovations.

The use of the life cycle assessment method is expected to increase in the building sector due to both European and national initiatives to take into account the climate change potential of our buildings. This increased use of LCAs indicates that there will be an increase of information and data for future investigations and assessments of the environmental impact of buildings. The LCA as a method is still evolving and adapting and will become a useful tool in all the processes of a building's life cycle. A further development of the implementation of the regulations for climate declarations could, in the future, also include existing buildings.

In this thesis, only the climate change potential has been included in the environmental impact assessment. In an LCA, several different environmental impact categories can be included. According to the standard that is used when conducting an EPD, the relevant environmental impacts that should be included, and how the results of their affects should be presented, are stipulated. The performed assessment in this thesis, could be carried out for other environmental impact categories. However, in making a decision on what alternative that has the lowest environmental impact, becomes more complex when assessing several

environmental impact categories. This complexity would need to be addressed in such an assessment.

7 Reflections

During the work on this thesis the research field of sustainable renovation has kept evolving. Some of the research that was performed early in the process of this thesis, the research field has moved past and further fulfilled the research gaps that was there in the beginning of this project. Being part of the strong research environment SIRen, has given me an insight on research with different perspective on sustainable renovation and I have seen the impressive results that was achieved in the research environment as well as side projects.

It has not just been the research field surrounding this thesis that has evolved over time but also this studies scope. The evolution of the scope of the research carried out during the work on this thesis has influenced the results in several ways. Initially, the research had a broad perspective, aiming to include the whole renovation process and all sustainability aspects. Over time, more focus was placed on some specific aspects. This does not necessarily make other aspects of the renovation process less important, but it did lead to this research becoming more focused. The focus also narrowed down to targeting building owners, primarily at the beginning of a renovation process and also regarding the evaluation of the renovated building.

The literature review shows that there is a clear focus on energy issues in research connected to renovations. This is also shown in the introduction to this thesis. Some information was found about the technical status of the building stock but most references focussed on discussing the energy needs in existing buildings. The introduction in this thesis does, therefore, not give a holistic view of sustainable renovations. In Section 1.1.2 the different aspects within the three main categories are discussed, but these do not cover every issue. Detailed studies can be found for single parameters, such as the cultural values of buildings and profitability calculation models etc. These are highly relevant but need to be integrated with other research to give a comprehensive view of what is available today to achieve more sustainable renovations.

The study carried out in Paper III aimed at looking at what information that was available and how the situation was dealt with when information was missing. Information of interest could, for example, have been about the structure of an existing building so that its heat conductivity (U-value) could be established. What the study finally concluded was that information is seldom well-documented in a renovation project. If the aim of this study had been to analyse how information was

documented and gathered from building owners, the questionnaires and methods could have been adapted appropriately. I believe that such a study would have shown a more complete picture regarding information handling.

During my PhD studies, I have had the opportunity to follow discussions about different perspectives of sustainability. What has been evident to me is that sustainability, or being sustainable, is not a steady state condition that can be easily reached. On the contrary, it is a process that needs to be continually maintained. The concept of sustainability will, for a considerable future, keep evolving. Future research and experiences will change and, hopefully, improve our views on sustainability and help us to find a balance between a reasonable level of fulfilling human needs and the use of the resources that are available on the planet without contributing to the negative environmental impact.

I believe that the concept of sustainable renovation within the categories of environment, economic and social sustainability, has been developed sufficiently to support the work within the building sector. But the aspects can all be further developed and will need to continue to adapt to developments in research and in the society.

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Appendix 1: Popular science summary

Assessment of sustainability aspects when making pre-renovation decisions

Approximately one third of all multi-family buildings in Sweden are in need of comprehensive renovations (Johansson, 2017). The most common grounds for carrying out renovations are acute technical issues or the expiring life span of the building or building components (Thuvander et al., 2016). Together with high costs for maintenance and operation, a high energy demand is also a common reason for building owners to carry out renovations in their building stock.

The European Union´s (EU) strategy, to reduce energy use and greenhouse gas emissions from the building sector, include the initiative "Renovation wave" (European commission, 2020). Greenhouse gas emissions can potentially impact our climate. To lower the impact, goals are formed to all sectors. The construction and real estate sector has been found to be among the greatest contributors to greenhouse gas emissions and therefore this sector is important to improve (Eurostat statistics, 2018).

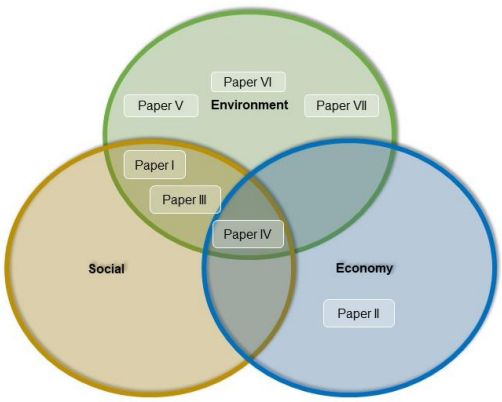
Buildings are our most complex and durable consumer goods (Lichtblau 2014). Subsequently, in renovation projects, decision-making is also a complex matter and during the initial evaluation phase of a renovation project there is often a lack of time, knowledge, information and tools (Olsson et al., 2015; Thuvander et al., 2012). Furthermore, each aspect of a renovation project needs to be evaluated, not only on its own, but also as an integral part of a larger whole (Kohler & Hassler, 2002; Thuvander et al., 2012). Kohler and Hassler (2002) emphasize the importance of the interrelationships between the different aspects of the management of the building stock from a sustainable development perspective.

Sustainability and how sustainability aspects are taken into consideration varies within the building industry (McKenzie, 2004). Different actors involved in the renovation process have different perspectives on the process and therefore have different needs for knowledge.

When aiming for sustainability, interdisciplinary understanding is a key factor. Not only is the integration of different aspects, such as environmental, economic and social issues, of great importance but also the integration of the different disciplines within each aspect (Wilkinson et al., 2014). Due to the uncertainties concerning the term 'sustainability', it will here be treated as in concept to be used when comparing different options, where an option could be 'a

more sustainable renovation' rather than the more exact term 'a sustainable renovation'.

In order to carry out this study, a number of sustainability aspects were chosen to be focused on. Within the category 'economic aspects', the main focus was on energy costs and profitability in Paper II. The environmental aspect of energy use was included in all Papers and climate change potential was included in Paper V-VII. Social aspects, such as indoor environmental quality and user involvement, were discussed in Paper IV as well as other social aspects that came to light during the performed case study.



The main questions throughout this thesis are if sustainable aspects are treated and managed in a systematic way in pre-renovation decision. Seven studies were performed by using different methods, such as case studies, surveys, action research, documentation, and literature studies as well as simulations and sensitivity assessment in LCA.

In Paper I, a literature review of 87 papers showed that there are several strategies to support sustainability in a renovation process. The issue does not seem to be lack of strategies but rather the implementation of developed strategies. To follow-up and evaluate the effect of the strategies and to further develop them seems to be lacking.

This thesis includes two different studies in which previous renovations were analysed (Paper II and Paper III). In both studies, it was evident that information from earlier renovations was limited. It seems, in these cases, that there is a lack of systematic documentation about how the information before a renovation was generated. Information seems to be missing or linked to an individual person. Return of experience is therefore vulnerable as people change jobs or retire. This also restricts the dissemination of information about the experiences gained to those involved in future renovation projects.

In (Paper IV) one case study was analysed by action research of the early phase of a school renovation (Paper IV). During the initial discussions it was evident how important earlier experiences were in the process. How the discussions were carried out are, to a great extent, due to the earlier experiences from other renovations, that the included participants have been a part of. Hastig & Tapper Jansson (2014) also concluded that a performance of a

renovation project was due to participants earlier experiences.

In Paper V-VII climate change potential for energy renovation measures was assessed. Taking into account the mix of energy sources that is relevant for the specific cases, making a assumption on the future energy mix as well as making a conscious decision on which material that is used, are important factors to consider since they will all influence the climate change potential of the energy efficient measure.

The results showed that if the energy mix is assumed to change in the future, with less fossil fuel and more renewable sources for electricity, the assessment of energy renovation measures is important to perform. The minimum and maximum variation in materials´ climate change potential show that assessment of different choices of materials should always be carried out before a renovation measure is performed.

I believe that the concept of sustainable renovation within the categories of environment, economic and social sustainability, has been developed sufficiently to support the work within the building sector. But the aspects can all be further developed and will need to continue to adapt to developments in research and in the society.

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ISBN 978-91-85415-17-5
ISSN 1652-6783
ISRN LUTVDG/TVIT-22/1005-SE(203)