Linköping Studies in Science and Technology
Dissertation No. 2008

Energy renovation of multi-family buildings in Sweden

An evaluation of life cycle costs, indoor environment and primary
energy use, and a comparison with constructing a new building

Lina La Fleur

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Abstract

Residential buildings account for 27% of the final energy use in the European Union. In cold climates, space heating represents the largest proportion of the energy demand in residential buildings. By implementing energy efficiency measures (EEMs) in existing buildings, energy use can be significantly reduced. The Energy Performance of Buildings Directive states that renovations of buildings offer an opportunity to improve energy efficiency. Renovations that include measures implemented with the specific purpose of reducing energy use are referred to as energy renovations. In addition to improving energy efficiency, an energy renovation can also improve the indoor environment. Sweden, like many other European countries, faces the challenge of renovating an ageing building stock with poor energy performance. Improving energy efficiency and performing energy renovations in a cost-effective manner is central, and optimization approaches are often used to identify suitable EEMs and energy renovation approaches. New buildings usually feature better energy performance compared to older buildings, and one approach for reducing energy use in the building sector could be to demolish old buildings with poor thermal performance and build new buildings with better thermal performance.

The aim of this thesis is to evaluate energy renovations of multi-family buildings with regard to space heating demand, life cycle costs, indoor environment and primary energy use. The choice between energy renovation of a multi-family building and the demolition and construction of a new one is also investigated with regard to life cycle costs (LCCs). A Swedish multi-family building in which energy renovation has been carried out is used as a case study. The building was originally constructed in 1961 and has a lightweight concrete construction. The renovation included improving the thermal performance of the building envelope and replacing the exhaust air ventilation system with a mechanical supply and exhaust air ventilation system with heat recovery.

The methods used in the studies include dynamic whole building energy simulation, life cycle cost analysis and optimizations, and a questionnaire on indoor environment perception. Extensive field measurements have been performed in the building prior to and after renovation to provide input data and to validate numerical predictions. In addition to the studied building, the analysis of the choice between energy renovation and the demolition and construction of a new building includes three other building construction types, representing common Swedish building types from the 1940s, 1950s and 1970s.

The analysis shows that the energy renovation led to a 44% reduction in space heating demand and an improved indoor environment. The indoor temperature was higher after the renovation and the perception of the indoor temperature, air quality and noise in the building improved. The EEMs implemented as part of the energy renovation have a slightly higher LCC than the optimal combinations of EEMs identified in the LCC optimization. It is not cost-optimal to implement any EEMs in the building if the lowest possible LCC is the objective function. Attic insulation has a low cost of implementation but has limited potential in the studied building with its relatively good thermal properties. Insulation of the façade is an expensive measure, but has a great potential to reduce heat demand because of the large façade area. Façade insulation is thus required to achieve significant energy savings. Heat recovery in the ventilation system is cost-effective with an energy saving target above 40% in the studied building. The primary energy factors in the Swedish Building Code favor ground source heat pumps as a heat supply system in the studied building.

The LCC of renovation is lower compared to demolishing and constructing a new building. A large proportion of the LCC of demolition and new construction relates to the demolition of the existing building. In a building with a high internal volume to floor area ratio, it is not always possible to renovate to the same energy performance level as when constructing a new building. A more ambitious renovation approach is also needed compared to a building with a smaller volume to floor area ratio.

Sammanfattning

Nära 27 % av den totala energianvändningen i den Europeiska Unionen sker i bostäder. I länder med kallt klimat används den största delen till uppvärmning. Genom att implementera energieffektiviseringsåtgärder i befintliga byggnader kan energiprestandan signifikant förbättras. Europeiska Unionens direktiv om byggnaders energiprestanda framhåller att ett tillfälle att förbättra byggnaders energieffektivitet finns då byggnader ska renoveras. Byggnadsrenoveringar som innehåller åtgärder som implementeras med det primära syftet att minska energianvändningen kallas ofta energirenoveringar. Utöver energieffektivisering kan energirenoveringar ofta förbättra inomhusmiljön i byggnaden. Som många andra Europeiska länder står Sverige inför utmaningen att renovera ett åldrande byggnadsbestånd med låg energiprestanda. Kostnadseffektivitet är centralt vid energirenoveringar och energieffektivisering och optimeringsansatser är vanliga för att identifiera vilka energieffektiviseringsåtgärder som bör implementeras. Nya byggnader har som regel bättre energiprestanda jämfört med äldre byggnader, och en ansats till att minska energianvändningen i byggnadssektorn överlag är således att riva äldre byggnader med låg energiprestanda och konstruera nya byggnader med bättre energiprestanda.

Syftet med denna avhandling är att utvärdera energirenoveringar av flerfamiljshus avseende effekterna på uppvärmningsbehov, livscykelkostnader, inomhusmiljö och primärenergianvändning. Valet mellan energirenovering kontra att riva och bygga en ny byggnad analyseras också utifrån ett livscykelkostnadsperspektiv. För att studera detta har en svensk flerfamiljsbyggnad som genomgått energirenovering studerats. Byggnaden konstruerades 1961 och har en lättbetongstomme. När byggnaden renoverades förbättrades prestandan hos byggnadens klimatskal och frånluftsventilationssystemet byttes ut mot ett balanserat mekanisk ventilationssystem med värmeåtervinning.

Metoderna som använts i studierna i denna avhandling är dynamisk byggandssimulering, beräkning och optimering av livscykelkostnader, samt en enkätstudie om hur de boende uppfattar sin inomhusmiljö. Omfattande mätningar har utförts i byggnaden och har använts som indata och för att validera resultaten. Utöver den studerade byggnaden har tre andra byggnadstyper inkluderats i analysen av valet mellan energirenovering och att riva och konstruera en ny byggnad. Dessa byggnadstyper representerar vanliga svenska byggnadstyper från 1940-, 1950- och 1970-talet.

Analyserna visar att den renovering som genomfördes i byggnaden ledde till en minskning av uppvärmningsbehovet med 44 % och en förbättring av inomhusmiljön. Inomhustemperaturen var högre efter renoveringen, och de boende

uppfattade temperaturförhållanden, luftkvalitet och bullersituationen som bättre efter renoveringen. De energieffektiviserande åtgärder som implementerades vid renoveringen gav en något högre livscykelkostnad än de åtgärder som identifierades som optimala genom livscykelkostnadsoptimering. Det är inte kostnadseffektivt att implementera några energieffektiviseringsåtgärder som del av renoveringen om den lägsta livscykelkostnaden är målsättningen. Vindsisolering är en förhållandevis billigt åtgärd att genomföra, men har begränsad potential i den studerade byggnaden vars vind redan har relativt god termisk prestanda. Fasadisolering kräver en större investering, men har större potential att minska energianvändning på grund av den stora fasadytan. Detta innebär att det är nödvändigt att isolera fasaden för att uppnå hög energibesparing. Värmeåtervinning i ventilationssystemet är kostnadsoptimalt om ett energibesparingsmål på mer än 40 % ställs på energirenoveringen. Primärenergifaktorerna i den svenska byggnadskoden gynnar bergvärmepump som energitillförselsystem i de studerade byggnaden.

Kostnaden för att energirenovera är lägre än att riva och bygga en ny byggnad. En stor andel av kostnaderna vid rivning och nybyggnation är kopplade till rivning och bortforsling av rivningsmassa. I byggnadstyper med stor inre volym i förhållande till uppvärmd golvyta är det inte alltid möjligt att energirenovera till en energiprestanda som är lika god som en ny byggnad. Det krävs också en mer ambitiös renovering för att uppnå samma energiprestanda som en byggnad med mindre inre volym i förhållande till uppvärmd golvyta.

List of appended papers

Paper I

La Fleur, L., Moshfegh, B., & Rohdin, P. (2017). *Chapter 39: Energy performance of a renovated multi-family building in Sweden*. In: Sayigh A. (eds.) *Mediterranean Green Buildings & Renewable Energy*. Cham: Springer.

Paper II

La Fleur, L., Moshfegh, B., & Rohdin, P. (2017). Measured and predicted energy use and indoor climate before and after a major renovation of an apartment building in Sweden. *Energy and Buildings*, 146, 98–110.

Paper III

La Fleur, L., Rohdin, P., & Moshfegh, B. (2018). Energy use and perceived indoor environment in a Swedish multi-family building before and after major renovation. *Sustainability* 10(3).

Paper IV

La Fleur, L., Rohdin, P., & Moshfegh, B. (2019). Investigating cost-optimal energy renovation strategies for a multi-family building in Sweden. Accepted for publication in *Energy and Buildings*.

Paper V

La Fleur, L., Rohdin, P., & Moshfegh, B. (2019). Energy renovation versus demolition and construction of a new building – a comparative analysis of a Swedish multi-family building. *Energies* 12(10).

“The difference between screwing around
and science is writing it down”

- Adam Savage

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List of abbreviations

BES	Building Energy Simulation
CO ₂ eq	Carbon dioxide equivalent
COP	Coefficient of Performance
DHW	Domestic Hot Water
EED	Energy Efficiency Directive
EEM	Energy Efficiency Measure
EPBD	European Directive on the Energy Performance of Buildings
HRX	Heat Recovery
IDA ICE	IDA Indoor Climate and Energy
IHG	Internal Heat Gains
LCC	Life Cycle Cost
LLCC	Lowest Life Cycle Cost
OPERA-MILP	Optimal Energy Retrofit Advisory-Mixed Integer Linear Programming
PE	Primary Energy
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
RQ	Research Question
SMHI	Swedish Hydrological and Meteorological Institute

Nomenclature

a	Number of years
A	Area, m^2
b	Number of years
CE_1	Inevitable maintenance cost of building envelope, SEK/ m^2
CE_2	Cost of thermal improvement of building envelope, SEK/ m^2
CE_3	Cost of thermal improvement of building envelope, SEK/ $m^2 \cdot m$
$C_{envelope}$	Cost of maintenance and thermal improvement of building envelope, SEK/ m^2
C_{HS}	Cost of heating system, SEK
C_p	Specific heat capacity, J/kg $^{\circ}C$
DH	Degree hours, $^{\circ}Ch$
DOT	Design outdoor temperature, $^{\circ}C$
E_{DHW}	Annual domestic hot water use, Wh
$E_{heating}$	Annual space heating demand, Wh
E_{HWC}	Annual heat losses from hot water circulation, Wh
HS_1	Cost of heating system, SEK
HS_2	Cost of heating system, SEK/kW
HS_3	Cost of support system for heating system, SEK/kW
N	Non-recurring cost, SEK
P_{IHG}	Internal heat gains, W
P_{max}	Design power of heating system, W
PV	Present value, SEK
$q_{exhaust}$	Ventilation exhaust air flow, m^3/s
$Q_{infiltration}$	Infiltration heat losses, W/K
$q_{infiltration}$	Infiltration air flow, m^3/s
q_{supply}	Ventilation supply air flow, m^3/s
Q_{total}	Total heat losses, W/ $^{\circ}C$
$Q_{transmission}$	Building envelope transmission losses, W/K
$Q_{ventilation}$	Ventilation heat losses, W/K
$q_{ventilation}$	Ventilation air flow, m^3/s
R	Discount rate, %
R	Annually recurring cost, SEK
RV	Residual value, SEK

T	Insulation thickness, m
$T1$	Ventilation air temperature after heat recovery, °C
T_b	Balance temperature, °C
$T_{exhaust}$	Ventilation exhaust air temperature, °C
T_{indoor}	Indoor temperature, °C
T_{out}	Outdoor temperature, °C
T_{return}	Ventilation return air temperature, °C
T_{supply}	Ventilation supply air temperature, °C
U	Overall heat transfer coefficient, W/m ² °C
η	Ventilation heat recovery efficiency
ρ	Density, kg/m ³

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1 Introduction

This section introduces the scope of the research and the motivation for the performed research. The aim of the thesis and the research questions are introduced and the appended papers and the research journey are briefly described.

We spend more and more time indoors, and buildings are important for our well-being. Not only do they provide shelter from the weather, they also provide a place for many of us to work, relax and perform many of the activities that are essential in our everyday life. Human comfort in buildings is dependent on our satisfaction with the indoor environment (Nilsson, 2003). To achieve a comfortable indoor environment, we usually have to supply energy to the building. Energy use in buildings represented 40% of the final energy use in the European Union in 2017, and energy use in residential buildings alone accounted for 27% of the final energy (European Commission, 2019). The largest part of the energy demand in buildings located in cold climates is used to achieve a comfortable indoor temperature. The space heating demand usually represents between 60% and 80% of the total energy demand in buildings in cold regions (Gynther, Lapillonne, & Pollier, 2015). It is widely agreed that energy should be used efficiently. Still, around 75% of existing buildings located in the European Union are energy inefficient in comparison with current building regulations (European Commission, 2018b), and improving energy efficiency in the existing building stock is an important challenge.

The European 2030 climate and energy framework states that greenhouse gas emissions should be reduced by 40% by 2030 compared to the 1990 level (European Commission, 2018a). The building sector is highlighted as the sector with the greatest potential for energy efficiency improvement (European Parliament, 2012). The European Energy Performance of Buildings Directive (EPBD) calls for energy efficiency to be improved when buildings undergo major renovation and for new buildings to be constructed with high energy performance to achieve a decarbonization of the building stock (European Parliament, 2018). The EPBD stress that the cost-effectiveness of energy efficiency measures (EEMs) is important, and that a cost-optimal balance between the reduction in energy use and the capital investment in EEMs should be identified (European Parliament, 2010, 2018).

Sweden, like the rest of the European Union, faces a challenge in terms of managing an ageing building stock and reducing the building sector's climate impact through improving energy efficiency. Nationally, Sweden aims to achieve zero net emissions of greenhouse gases by 2050, and to reduce energy use in the building sector by 50%

by 2050 compared to 1995 (The Swedish Government, 2010). Almost one third of the final energy use in Swedish buildings is in multi-family buildings (Swedish Energy Agency, 2018) and around half the heated area in Swedish multi-family buildings is in buildings constructed before 1970 (Swedish National Board of Housing Building and Planning, 2016). In 2014, it was estimated that more than half the apartment area in this segment remains in its original form or has undergone limited maintenance. The average energy use per square meter of heated area is also significantly higher in buildings constructed before 1980 (Swedish Energy Agency, 2017). This means that Sweden faces both the challenge of renovating a large proportion of its existing building stock and an opportunity to achieve a significant improvement in energy efficiency in the building stock. The long interval between instances of building renovation or maintenance means that if the opportunity to reduce energy use as part of building renovation is not seized, we will find ourselves locked into a carbon intense and energy inefficient building stock. Studies have addressed several barriers to the implementation of EEMs in building renovation, such as a lack of focus on costs during a building's life cycle and a lack of understanding about the effect on a building's energy use when implementing EEMs (Baek & Park, 2012; Palm & Reindl, 2018). Palm and Reindl (2018) also found that EEMs were implemented based on past experiences from what was perceived to be typical building energy renovations, rather than on the conditions in the actual building. This indicates that there is a need to increase understanding of the effects on a building from energy renovation and the life cycle cost (LCC) of implementing EEMs.

1.1 Motivation for the performed research

Although energy renovation has been studied extensively in previous research, few studies have performed numerical predictions and realistic empirical validations of building energy use and indoor climate before and after renovation. Previous studies also indicate a lack of understanding about the effects of energy renovation among stakeholders performing renovations. The research presented here thus provides a holistic approach for understanding the effects on energy use and indoor environment, as well as the LCC of energy renovations with different energy saving targets. There is also limited research regarding the choice between energy renovation and demolishing ageing buildings and constructing new buildings. This thesis includes an LCC investigation comparing energy renovation with demolition and constructing a new building.

1.2 Aim and research questions

The aim of this thesis is to evaluate energy renovations of multi-family buildings with regard to space heating demand, primary energy use, indoor environment and LCC, and to analyze different approaches for reducing energy use in the building stock. Two main approaches to energy reduction in the building stock are considered and analyzed from a LCC perspective: implementing EEMs in existing buildings through energy renovation, and demolishing an old building and constructing a new building with better energy performance. The effect on the surrounding energy system is analyzed using primary energy factors (PE factors). A case study was performed on a building that underwent an energy renovation to study the effect on the building regarding energy use and the indoor environment. The following research questions (RQs) are answered:

- 1) What is the measured and predicted space heating demand and perceived indoor environment before and after energy renovation, and how do the predicted results compare to the measured data?
- 2) What is the LCC and impact on primary energy use of implementing cost-optimal EEMs to achieve different energy saving targets during building renovation?
- 3) What is the LCC of demolishing an old building and constructing a new building with modern energy performance compared to the LCC of energy renovation of an existing building?

1.3 Research journey and methodological approach

This thesis is the result of two research projects. The main research project has been “Doing CAREER – Energy efficiency in million-program building renovation: a collaborative research program for integrative knowledge development”, financed by the Swedish Research Council FORMAS. The research project studied the renovation of a district heated multi-family building during the planning phase, during the actual renovation and after the renovation, to allow for an in-depth analysis of the effect of an energy renovation on a building’s energy use and indoor environment. Two PhD students were involved in the project. The PhD students attended the planning meetings for the renovation as observers. All decisions on renovation measures were made by the housing company and contracted consultants.

Extensive data collection from measurements, questionnaires and external sources was performed prior to and after the renovation. The data formed the foundation for the research presented in this thesis. Two reference apartments were used, where

measurements could be performed on apartment level. The data collection was used for an extensive evaluation of the energy renovation that took place in the building in terms of the effect on energy use and the indoor environment (Papers I-III). In addition, alternative energy renovation approaches were analyzed using an LCC optimization approach (Paper IV). Building on the experience from Papers I-IV, the research continued within the ongoing FORMAS project “Public buildings – Renovation or new construction”, where the building studied in Papers I-IV was used to develop a methodological approach to analyze LCC for energy renovation versus demolition and constructing new buildings (Paper V).

Whole building energy simulation (BES) has been a foundation for many of the results presented in the appended papers. A BES model was constructed, and simulations of energy use and indoor climate were performed using the dynamic simulation software IDA ICE versions 4.6, 4.7 and 4.8. The indoor temperature, carbon dioxide (CO₂) levels in the main bedroom and household electricity use were measured in the reference apartments prior to and after energy renovation, in order to be used as a basis for estimating user behavior in the studied apartments. The airtightness was also measured to estimate infiltration heat losses and local climate data was collected at the building site. The model was empirically validated against measured data. The simulated indoor temperature was compared to the measured indoor temperature to validate the accuracy of the numerical prediction. The simulated monthly space heating demand was compared to the measured space heating demand to validate the accuracy of predicting heat demand at building level. The validated BES model was used for detailed studies of the indoor climate in the building prior to and after the energy renovation. The simulations were supplemented with a questionnaire on the residents’ perceptions of the indoor environment prior to and after the energy renovation. Once the technical evaluation of the energy renovation had been performed, the energy renovation was evaluated with regard to its cost-effectiveness using the optimization tool OPTimal Energy Retrofit Advisory Multiple Integer Linear Programming (OPERA-MILP). OPERA-MILP identifies combinations of EEMs that together achieve the lowest LCC for a building during a selected life cycle. Including different maximum energy uses for the building as constraints made it possible to evaluate the energy renovation in terms of its cost-effectiveness and to identify which combinations of EEMs were cost-optimal to implement depending on the energy saving target for the building. In addition to district heating as an energy supply system, a comparison was made with a ground source heat pump as an alternative system. The LCC relating to demolishing the building and constructing a new building were investigated, and an analysis of the cost of energy renovation versus demolition and new construction was performed as an alternative approach to reducing energy use in the existing building stock. The analysis focused on the building body, and excluded those parts of the building that have no effect on the energy use, such as interiors, installing

elevators, control systems, etc. The geometry of the studied building was used, and four different building construction types that are common in the Swedish building stock were studied.

The resource intensity of the renovated building was analyzed in Paper II using PE factors. In this thesis, the analysis is extended to include the LCC optimal energy renovations and the two heating systems included in the analysis in Paper IV (district heating and ground source heat pump). PE factors from 2018 for different Swedish district heating systems are used for comparison. A comparison is also made with the PE factors used in the Swedish building code.

1.4 Overview of papers

The thesis builds on the results from the following five papers:

Paper I

La Fleur, L., Moshfegh, B., & Rohdin, P. (2017). *Chapter 39: Energy performance of a renovated multi-family building in Sweden*. In: Sayigh A. (eds.) *Mediterranean Green Buildings & Renewable Energy*. Cham: Springer.

The book chapter presents a dynamic model of the studied building and empirical validation with regard to the model's ability to predict indoor temperature and space heating demand. Although the model predicts indoor temperature and heat demand accurately prior to energy renovation, there are discrepancies in modelled and predicted heat demand in the renovated building. An analysis was thus performed to discuss whether this could be related to user behavior (excessive airing) or the efficiency of the heat recovery unit in the new balanced mechanical ventilation system.

Paper II

La Fleur, L., Moshfegh, B., & Rohdin, P. (2017). Measured and predicted energy use and indoor climate before and after a major renovation of an apartment building in Sweden. *Energy and Buildings*, 146, 98–110.

The paper presents full empirical validation of a dynamic BES model using measured indoor temperature and actual space heating demand over the course of one year prior to and after renovation of the studied multi-family building. Building on the discussion from Paper I, the heat recovery efficiency of the ventilation system was measured and identified as the reason for differences in predicted and measured heat demand after energy renovation. Paper II also includes a sensitivity analysis regarding user behavior, windows' solar heat gain factors, heat exchanger efficiency,

and building envelope transmission losses. Primary energy use and climate impact as a result of the energy renovation are investigated and discussed.

Paper III

La Fleur, L., Rohdin, P., & Moshfegh, B. (2018). Energy use and perceived indoor environment in a Swedish multi-family building before and after major renovation. *Sustainability* 10(3).

The paper builds on a questionnaire on perceived indoor environment prior to and after carrying out energy renovations in the studied building. A dynamic simulation of indoor thermal comfort is performed with the validated BES model from Papers I-II. The effect on thermal comfort is studied in a sensitivity analysis including different indoor temperature set points, windows' solar heat gain factors and different internal heat gains.

Paper IV

La Fleur, L., Rohdin, P., & Moshfegh, B. (2019). Investigating cost-optimal energy renovation strategies for a multi-family building in Sweden. Accepted for publication in *Energy and Buildings*.

The energy renovation that was performed in the studied building is evaluated with regard to LCC by investigating which EEMs are cost-effective to implement with different energy saving targets in the studied building. The LCC optimization tool OPERA-MILP is used to identify the optimal EEMs. The LCC is calculated for energy saving targets ranging between 10% and 70%. BES is used to validate the heat demand predicted in OPERA-MILP.

Paper V

La Fleur, L., Rohdin, P., & Moshfegh, B. (2019). Energy renovation versus demolition and construction of a new building – a comparative analysis of a Swedish multi-family building. *Energies* 12(10).

A comparison is made between the LCC of energy renovation versus demolition and constructing a new building. The geometry of the studied building is used to create four different building construction types with different thermal performances. OPERA-MILP is used to identify cost-optimal combinations of EEMs in the four building types. The LCC is investigated for energy saving targets ranging between 10% and 70% in all four building types. The LCC of demolishing the four building types and constructing a new building that fulfills the requirements of the Swedish Building Code is calculated for the building body and compared to the LCC of energy renovation.

All papers consider the effects of energy renovation on a building. Papers IV and V do not consider the effect on indoor environment, focusing instead on the effect on space heating demand. LCCs, optimal energy renovation strategies and alternatives to energy renovation are considered in Papers IV-V. The focus of each of the appended papers in relation to the RQs are summarized in Table 1.

Table 1. Focus of included papers.

	Paper I	Paper II	Paper III	Paper IV	Paper V
RQ 1	×	×	×	×	×
RQ 2		×		×	×
RQ 3				×	×

1.4.1 Co-author statement

All papers were written by the author of this thesis. Professor Barham Moshfegh and Assistant Professor Patrik Rohdin supervised the work, and contributed valuable comments on the written text and guidance on assuring the validity of results. The research design of all papers was developed jointly with Professor Moshfegh and Assistant Professor Rohdin. The thesis author performed simulations, calculations, optimizations, and analysis of the results. Measurements were carried out by the thesis author with assistance from measurement technician Jakob Rosenqvist. The data was processed by the thesis author. An existing questionnaire from the Department of Occupational and Environmental Medicine at Örebro University Hospital in Sweden was used. The questionnaire on perceived indoor environment was distributed and collected by two former master’s students – Sofia Rehn and Martin Skoglund – prior to the energy renovation of the building, and by the thesis author after energy renovation. The responses were compiled and analyzed by the author of this thesis. Four former master’s students – David Mowitz, Johanna Niklasson, Kristoffer Palm and Cassandra Wu – performed a pilot study of the choice between energy renovation and demolition and constructing a new building. The study included in Paper V was performed by the authors of this thesis. Data on the building (such as blueprints, energy statistics and operational data) was obtained from documentation provided by the property owner and processed by the thesis author.

1.5 Scope and delimitations

In this thesis the term ‘energy renovation’ is used to describe renovations that include measures performed with the specific purpose of reducing energy use, regardless of the magnitude of the energy efficiency improvement. Renovation measures of this kind are referred to as ‘energy efficiency measures’ (EEMs). The

main focus is on measures to reduce space heating demand in multi-family buildings in need of renovation. Any reference to a reduction in heat demand therefore refers to the reduction in space heating demand.

The included papers focus on residential multi-family buildings, and are based on a case study of a renovated multi-family building in Linköping, Sweden. District heating as energy supply system has been the main focus, since the building is located within a district heating network. A ground source heat pump has been considered as an alternative heating supply system in Paper IV. Other energy supply systems, such as a wood boiler or other heat pump solutions, are not considered. The thesis focuses on the effect at building level. The effect on surrounding energy systems is discussed in relation to the primary energy use. The system boundary used in the studies and what can be studied with the chosen system boundary are discussed in section 2.1.

A comparison is made between energy renovation and constructing a new building using a LCC analysis. However, no life cycle analysis determining the resource intensity and the environmental impact of the two alternatives is performed. Instead, only primary energy use to cover the energy demand is considered in relation to the resource intensity of the building. The costs used to investigate the LCC are based on data from Wikells byggberäkningar (Wikells Byggberäkningar AB, 2018), and are hence based on a Swedish context. How the cost could vary depending on where in Sweden and where within the city the building is located has not been considered, and could affect the results for other buildings or contexts. The studied building is a rental multi-family building owned by a municipal housing company. The building is connected to the district heating network, which is also municipally owned. In a municipality without district heating or with a privately owned district heating network, the choice of heating system or implemented EEMs could be different. The focus is on the LCC, and other values or benefits related to newly constructed buildings and renovated buildings are not considered.

It should also be noted that the methods for predicting energy use vary between the papers. This means that the predictions for heat demand have been performed with different levels of accuracy and may thus yield slightly different values. BES modelling allows for a higher degree of detail regarding input data and thus the results achieved. When any calculation approach is used, input data and time steps must be simplified. This means that the accuracy when predicting heat demand is lower, although the method requires significantly less time. This will be further discussed in section 5.

2 Building energy systems

This section provides a theoretical introduction to ways of analyzing buildings as energy systems. The section also includes a description of the heat balance, indoor environment and thermal comfort in buildings.

2.1 The used system perspective

A system can be defined as components that are connected to each other so that, together, they perform a function or a certain activity, the total system objective (Churchman, 1968). The components within the system are isolated from their surrounding environment by a system boundary. The resources available within the system boundary allow the components to perform their specific action or activity towards achieving the total system objective. The surrounding environment is not within the control of the system, yet it has an essential impact on the system by adding constraints and offering the conditions for the system to function within. An illustration of a system can be seen in Figure 1.

Figure 1. Illustration of a system consisting of connected components within a defined system boundary from its surrounding environment.

The division into system components is common when using this type of approach, and is done to be able to determine and evaluate whether the system works properly, i.e. works towards the total system objective (Churchman, 1968). To be able to do this, it is important to have measures of performance to establish that individual components and the whole system work.

The overall objective of a building is to provide shelter for the people living in the building. The objective of a building's energy system is to provide a comfortable indoor environment within the building. Thermal comfort and good indoor environment are important measures of performance in a building's energy system. For property owners, an important aspect is that a good indoor environment is achieved as cost-effectively as possible. An important measure of performance is thus low use resources, for example energy. It is common for detailed studies of building energy systems to have the system boundary around the building. Components within the building that are essential for providing a good indoor environment and components that affect the indoor environment are essential when describing the system. This means that aspects such as the heat losses from transmission through the building envelope, ventilation and infiltration of air, demand for heating and domestic hot water (DHW), and internal heat gains (IHGs) will be central aspects in this thesis. Figure 2 illustrates components that are usually included in studies at building level in residential buildings in cold climates. In warm climates, cooling is sometimes used in residential buildings and is then also important when describing the system. Cooling of residential buildings is uncommon in Sweden.

Figure 2. A common system boundary for studies of building energy systems. Adapted from Swedish National Board of Housing Building and Planning (2012).

The outdoor climate constitutes an essential part of the environment outside a building’s system boundary. The outdoor climate will affect the system and the heat demand of the building to a large extent. The system has no influence on the climate. Outside the system boundary, there is also a system that supplies the building with energy, for example a district heating system or an electricity grid. The building’s energy system is dependent on the surrounding energy system to have a steady energy supply. The building has no influence on the energy supply system, such as what type of fuel is used to generate heat or electricity. The building thus has no influence on the resource intensity of the energy supplied to the building, only the amount of energy that is used. However, if a system analysis is performed of a city’s or a region’s energy system, buildings would be an important component since they constitute a demand for energy, and would thus be essential for the total system objective the energy system.

The articles included in the thesis are primarily focused on the building level, by studying heat demand, indoor environment and the LCC of building energy renovations. The system boundary is thus around the building body. The approach presented in Figure 2 means that the focus when studying the building is on the connection and interlinkages between components within the building, such as how IHG and changes in the thermal performance of the building affect the heat demand. The surrounding energy system is important since it supplies energy to the building, but the effects on the energy system from changes in heat demand are not central in the analysis. One approach for considering the broader effect of the energy use in a building is to consider the primary energy demand in addition to the supplied energy at building level. Primary energy is an energy source that has not undergone any conversion or transfer (United Nations, 2017; UNSD, 2019), for example raw fuels or biomass. The primary energy has to be converted into an energy carrier suitable for the purpose, such as motor fuel or electricity. Different energy carriers will be more or less intense in terms of primary energy use. Energy carriers converted from, for example, waste or biomass are generally considered to have low primary energy use. Common energy carriers in a building context are heat (e.g. district heating) and electricity. By considered the primary energy use of the building, the system boundary is widened. Section 5.3 further describes primary energy, and common approaches for considering primary energy using primary energy factors are introduced. The connection between primary energy and final energy use in a building can be seen in Figure 3.

Figure 3. Basic connection between primary energy use and final energy use in buildings.

In the context of energy renovation, the implementation of energy efficiency measures and the choice of energy supply system will have significant impact on the final energy use in the building, which in turn will affect the amount of primary energy needed. Depending on the energy carrier used to supply energy to the building, the primary energy use will vary.

2.2 The energy balance of a building

Energy is supplied to buildings to achieve a comfortable indoor temperature, to heat DHW and for household activities and facility functions (Abel & Elmroth, 2012; Hagentoft, 2001; Nilsson, 2003; Warfvinge & Dahlblom, 2010). Energy for space heating and DHW represents a significant proportion of the total energy use in buildings in cold climates. Whereas the heat demand for DHW is directly related to the amount of hot water used, the space heating demand is mainly dependent on the outdoor temperature and the heat losses, but also on how the building is used.

2.2.1 Heat losses

Heat losses occur from transmission through the building envelope, air exchange from ventilation of the building, and air leakage via infiltration through cracks, gaps and holes in the building envelope¹. The total heat losses, Q_{total} , are seen in Equation 1.

$$Q_{total} = Q_{transmission} + Q_{ventilation} + Q_{infiltration} \quad [1]$$

where $Q_{transmission}$ are the losses from transmission of heat through the building envelope via conduction (W/K), $Q_{ventilation}$ are the losses from ventilation of the building (W/K), and $Q_{infiltration}$ are the losses from undesired air leakage in the building envelope (W/K).

The transmission losses are dependent on the thermal properties of the building envelope, and are calculated in Equation 2.

$$Q_{transmission} = \sum_{i=1}^n (U_i \times A_i) \quad [2]$$

where U_i is the overall heat transfer coefficient of a building part² (W/m²·°C), and A_i is the area of the building part (m²).

To achieve good indoor air quality, fresh air is supplied to the building via natural or mechanical ventilation. In a balanced mechanical ventilation system, air is supplied

¹ Sections 2.2.1-2.2.3 are based on Warfvinge & Dahlblom (2010) and Abel & Elmroth (2012) unless some other reference is given.

² Including thermal bridges.

and extracted mechanically. This allows the possibility to install a heat recovery system where the exhaust air is used to preheat the supply air. The losses from ventilation can thus be significantly reduced. Rotary heat exchangers and plate heat exchanger are common in residential buildings. The heat recovery efficiency depends on the type of system, and the highest efficiency is achieved with a rotary heat exchanger (up to 85% in a laboratory setting). Plate heat exchangers have no moving parts and are less likely to transfer pollutants from exhaust air to supply air, but the efficiency is lower (around 60%). The losses from ventilation are calculated in Equation 3.

$$Q_{ventilation} = (1 - \eta) \times q_{ventilation} \times \rho \times C_p \quad [3]$$

where η is the efficiency of the ventilation heat recovery, $q_{ventilation}$ is the ventilation air flow (m^3/s), ρ is the density of air (kg/m^3) and C_p is the specific heat capacity of air ($\text{J}/\text{kg}\cdot^\circ\text{C}$).

Air leakage occurs in the building envelope through gaps, cracks or holes, and is referred to as infiltration. Infiltration is driven by wind pressure on the building envelope, by pressure differences created by a difference in temperatures inside and outside the building (density difference), and by mechanical ventilation components creating a pressure difference. The amount of infiltration in a building is often hard to estimate, but can be approximated. One of the more common methods is to use the blower door technique³, where the air leakage at a mechanically induced pressure is measured and used to estimate the air leakage under normal pressure. When the infiltration flow at normal pressure has been approximated, the infiltration losses are calculated in a similar way to the losses from ventilation, but do not allow for heat recovery, see Equation 4.

$$Q_{infiltration} = q_{infiltration} \times \rho \times C_p \quad [4]$$

where $q_{infiltration}$ is the infiltration flow (m^3/s) induced by wind pressure, temperature difference, or mechanical forces.

³ The blower door technique is describes in International Standard ISO 9972-2015 “Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method” (International Standard ISO 9972-2015)

2.2.2 Heat demand

Heat has to be supplied to the building to compensate for the heat losses when there is a heat deficit. Part of the heat demand is covered by IHGs in the building, from people, appliances and solar radiation. The rest has to be actively supplied from the building's heating system. The heat that has to be supplied annually to the building for space heating purposes, $E_{heating}$ (Wh), is described in Equation 5.

$$E_{heating} = Q_{total} \times DH + E_{DHW} + E_{HWC} \quad [5]$$

where DH is the heating degree hours during one year ($^{\circ}\text{Ch}$), E_{DHW} is the annual DHW use (kWh), and E_{HWC} is the annual heat losses from hot water circulation⁴ (kWh).

The number of heating degree hours during one year is determined based on the hours in the year when the outdoor temperature is lower than the balance temperature. The balance temperature is the outdoor temperature when the heat losses from the building are equal to the IHGs in the building. When the outdoor temperature is above the balance temperature, no heat has to be supplied to the building to reach the desired indoor temperature. The heating degree hours are calculated using Equation 6.

$$DH = \sum_{i=1}^n ((T_b - T_{out_i}) \times \Delta t) \quad [6]$$

where T_b is the balance temperature ($^{\circ}\text{C}$), T_{out} is the outdoor temperature ($^{\circ}\text{C}$), and t is time (h).

The balance temperature for the whole year is calculated with Equation 7.

$$T_b = T_{in} - \left(\frac{P_{IHG}}{Q_{total}} \right) \quad [7]$$

where T_{in} is the indoor temperature ($^{\circ}\text{C}$), and P_{IHG} is the average power of IHG from people, appliances and solar radiation (W).

The annual heat demand calculations in Equations 5-7 represent a simplified method for predicting energy use in a building. Although they can give relatively accurate estimates of the annual heat demand, they offer limited possibilities to analyze space heating demand or the indoor climate in detail. Since IHG vary over the course of the year, the internal heat characteristics will also vary. The relationship between the indoor temperature, outdoor temperature and balance temperature is visualized in

⁴ Losses from hot water circulation has not been considered in the papers included in this thesis.

Figure 4. The blue area presents the heat deficit when active heating is required. The internal heat characteristics depend on the heat losses from the building and the IHG generated by the use of appliances, occupants present in the building and solar radiation. With small losses and a high amount of IHG, the heat deficit will be small since a large proportion of the losses is compensated for with the IHGs. The balance temperature will occur at a different outdoor temperature depending on the heat losses, IHG and desired indoor temperature. When the outdoor temperature is higher than the balance temperature, a heat surplus occurs which means that there is a risk that the indoor temperature will be higher than desired indoor temperature set point unless cooling is supplied or adaptive measures are taken to reduce the IHG, such as solar shading.

Figure 4. Relationship between the indoor temperature, outdoor temperature and balance temperature. Adapted from Abel and Elmroth (2012).

When any changes are made to a building, such as thermal improvements or changes in use, the internal heat characteristics will be affected and the balance temperature will also change. For detailed studies of building heat demand and indoor climate, a whole building energy simulation (BES) is a commonly used tool and is described further in Section 5.

2.2.3 Heating systems and design heating power demand

An overview of components in a building's heating system is seen Figure 5. District heating is the dominant energy carrier in heat supply systems in multi-family buildings in Sweden (Swedish Energy Agency, 2018), but buildings using various

kinds of heat pump solution have become increasingly common. Many Swedish buildings are heated with hydronic distribution systems, with radiators as room heating units. The power output to the zone is regulated using thermostats. In buildings with exhaust and supply air ventilation, the supply air is heated in order not to cause discomfort in the zone.

Figure 5. Components in a heating system. Adapted from Abel and Elmroth (2012).

The design power, P_{max} (W), for the heat supply system in a building is determined in Equation 8.

$$P_{max} = Q_{total} \times (T_{in} - DOT) \quad [8]$$

where DOT is the winter design outdoor temperature ($^{\circ}\text{C}$). If the building has heated supply air and room units, parts of the heat will be supplied in the air handling unit and parts will be supplied to the zone via the room heaters.

2.3 Indoor environment

The indoor environment refers to the temperature conditions, air quality, noise, and daylight conditions in a building. A well-functioning indoor environment is essential for a good quality of life. Zalejska-Jonsson and Wilhelmsson (2013) found a correlation between residents' overall satisfaction with their home and satisfaction with thermal comfort, sound and air quality in the building. A Danish study identified a comfortable indoor temperature as being just as important as good indoor air quality (Mortensen, Heiselberg, & Knudstrup, 2018). The study also found that draught is an important problem related to the indoor climate. Poor indoor environment has been identified as a common reason for renovating buildings (Femenías, Mjörnell, & Thuvander, 2018; Jensen, Maslesa, Berg, & Thuesen, 2018).

Changes in a building, such as an energy renovation, can have an impact on the indoor environment. Thomsen et al. (2016) studied the renovation of an apartment building near Copenhagen and found that the renovation improved both how the residents perceived the indoor climate and the indoor air quality, but did not improve the noise situation. Liu, Rohdin, and Moshfegh (2015) also found that the indoor environment was better in a renovated building and that there were fewer symptoms

that could be related to a poor indoor environment, compared to a similar building that had not undergone renovation. Leivo et al. (2016) showed that the percentage of occupants who were satisfied with the indoor air quality was higher after renovation in a study including 46 Finnish buildings.

A common cause of problems relating to poor thermal comfort in buildings during the winter is draughts, but very high or low surface temperatures can also be perceived as uncomfortable (Nilsson, 2003). Several studies have shown that the thermal comfort during the winter is perceived as better after an energy renovation that includes improving the thermal performance of the building (Prasauskas, Martuzevicius, Kalamees, & Kuusk, 2016; Thomsen et al., 2016). However, studies have also shown that problems can arise with poor thermal comfort related to high indoor temperatures during the summer in buildings with high thermal performance. In a study of 22 apartments in 16 newly constructed Estonian buildings, Simson, Kurnitski, and Maivel (2017) found problems with high indoor temperatures and that national thermal comfort requirements were not fulfilled during the summer. Using a dynamic simulation, they showed that it is possible to achieve an acceptable level of thermal comfort during the summer without active cooling. Passive measures including external solar shading were the most effective way to reduce indoor temperatures. Chvatal and Corvacho (2009) also demonstrated that although the energy efficiency and thermal comfort during the winter were improved after increasing the insulation level of the building envelope, the risk of overheating during the summer was significantly higher in Portuguese buildings. They concluded that avoiding solar radiation is essential in order to avoid active cooling.

2.3.1 Predicting thermal comfort

Providing a good level of thermal comfort is the primary function of a building's heating system. The most common approach to predicting thermal comfort is described in ISO standard 7730 on the comfort index of predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) (International Standard ISO 7730:2005, 2005; Nilsson, 2003). The index was developed by P.O. Fanger in the 1970s and is commonly referred to as Fanger's comfort index. Four factors related to thermal properties of the room are central to the thermal comfort model described by Fanger: air temperature, relative humidity, thermal radiation from surfaces in the room, and air velocity. In addition to properties in the room, two factors relating the person are also important: metabolic rate depending on activity level, and the thermal insulation from the clothing that the person is wearing. The PMV index is based on the mean vote of the perception of the thermal environment of a large group of people. The thermal environment is rated on a scale ranging from -3 to +3, where the thermal environment is perceived as very cold at the lower end and very warm at the higher end. In the middle of the scale the temperature is perceived as

neutral and neither cold nor warm. The PMV can also be calculated. Based on the PMV, the number of people who are likely to be dissatisfied – the PPD – is calculated⁵. When the temperature is perceived to be neutral, five percent of the people in the room are predicted to be dissatisfied and this is thus the lowest PPD value in a building. The PMV and PPD index has been criticized due to its limited applications in different geographical settings and building types (van Hoof, Mazej, & Hensen, 2014). However, it remains a common tool in studies of thermal comfort and is used in studies of thermal comfort and is used in European standard EN 15251-2007 to define comfort categories of buildings (European Standard EN 15251-2007, 2007).

⁵ For calculations of PMV and PPD, see International Standard ISO 7730:2005 “Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria”.

3 Energy use in the residential building stock

This section describes energy use in existing buildings, with a focus on the European and Swedish building stocks. Previous research on ways to reduce energy use in the building stock by carrying out energy renovation or by demolishing and constructing new buildings is presented. Energy efficiency measures are presented for buildings in cold climates where a significant amount of space heating is needed.

The energy use in a building will vary depending on the building type and location. In residential buildings in cold climates, the largest proportion of the energy will be supplied to the building to achieve a comfortable indoor temperature. Energy use in buildings represents around 40% of the total energy use in the European Union (European Commission, 2019). In 2017, the residential sector represented 27% of the final energy use, see Figure 6.

Figure 6. Final energy use in the European Union between 1990 and 2017 (European Commission, 2019).

An important goal in the European Union is to decarbonize the building stock (European Commission, 2016). Globally, 82% of the total energy use in buildings was supplied by fossil fuels (UN Environment and International Energy Agency, 2017) and a large proportion of European buildings use energy from sources with a high primary energy demand and fossil origin, such as natural gas (European

Commission, 2016). The two main legislative instruments for improving the energy performance of buildings in the European Union are the Energy Efficiency Directive (EED) and the Energy Performance of Buildings Directive (EPBD). The EED identifies the building sector as the sector with the greatest potential for energy efficiency improvements and the need to increase the renovation rate is emphasized (European Parliament, 2012). Both the EED and the EPBD addresses the need for cost-effective renovation approaches and implementation of energy efficiency measures (EEMs) as part of building renovation (European Parliament, 2018).

3.1 Energy use in the Swedish building stock

The residential and service sector used almost 39% of the total energy use in Sweden in 2016 (Swedish Energy Agency, 2018), see Figure 7.

Figure 7. Final energy use in Sweden between 1970 and 2016 (Swedish Energy Agency, 2018).

The total final energy use in the Swedish residential and service sector has remained relatively stable since the 1970s (Swedish Energy Agency, 2018). Oil was the dominant energy carrier in 1970, and the use of electricity and district heating has increased since then, see Figure 8. Almost one third of the final energy use in the residential and service sector was supplied by district heating in 2016.

Figure 8. Final energy use in the residential and service sector in Sweden between 1970 and 2016 (Swedish Energy Agency, 2018).

District heating is the most common energy carrier in Swedish multi-family buildings and was used in 90.2% of all Swedish multi-family buildings in 2016, see Figure 9 (Swedish Energy Agency, 2018). Oil, which was used in almost half the multi-family buildings at the beginning of the 1980s, is now only used for heating purposes in 0.2% of all Swedish multi-family buildings. The total heat demand has decreased, while the heated area has increased, which indicates that the energy efficiency in the Swedish building stock has increased.

Figure 9. Energy use for space heating and heating of domestic hot water and heated area in Swedish multi-family buildings between 1983 and 2016 (Swedish Energy Agency, 2018).

While the heat demand has decreased since the 1980s, the electricity use in residential building and service sector has increased, see Figure 10. This is true for heating purposes as well as electricity used for domestic or building purposes.

Figure 10. Electricity use in the Swedish residential and service sector between 1983 and 2016 (Swedish Energy Agency, 2018)..

Multi-family buildings in Sweden have an average heat demand for space heating and domestic hot water of 135 kWh/m²·year (Swedish Energy Agency, 2017). The number is slightly lower for single-family buildings, which have an average heat demand of 106 kWh/m²·year. Older buildings have a higher heat demand than new buildings and, as can be seen in Figure 11, heat demand in multi-family buildings has continuously decreased in buildings constructed since 1981.

Figure 11. Heat demand for space heating and domestic hot water for single-family and multi-family buildings in Sweden by construction year (Swedish Energy Agency, 2017).

Between 1961 and 1975, Sweden had a high rate of new building construction and the era is often referred to as the record years (Swedish National Board of Housing Building and Planning, 2003). This means that Sweden has a large proportion of buildings with relatively poor energy performance. Many of these buildings are also in need of renovation since the construction or technical installations have reached the end of their technical lifetime (Swedish National Board of Housing Building and Planning, 2016). Sweden, like many other European countries, faces a challenge in terms of finding cost-effective strategies for renovating buildings of this kind (European Parliament, 2018; Swedish National Board of Housing Building and Planning, 2018a).

3.2 Energy efficiency improvements in the building stock

The term ‘efficiency’ is common in many fields, and is often connected to the performance of a process or system (Pérez-Lombard, Ortiz, & Velázquez, 2013). Energy efficiency often refers to achieving the maximum output from a system with minimal input, i.e. the useful effect from a system or process in relation to the amount of resource required to produce the effect. Energy use can be reduced either by improving energy efficiency or by conserving energy. Whereas energy efficiency means that we can have the same output from a smaller amount of energy or a larger output from the same amount of energy, energy conservation means that we save energy by achieving a smaller output, thus requiring less energy. In the context of building space heating, an energy efficiency improvement means that the building uses less energy for space heating by, for example, reducing heat losses by adding thermal insulation or by installing a more efficient boiler. We can also reduce space heating demand by reducing the indoor temperature. Reducing the indoor temperature does not improve the efficiency of the building, since we achieve a smaller output in terms of lower indoor temperature. However, since we use less energy we have implemented an energy conservation measure.

3.2.1 *Energy renovation*

Buildings need to be regularly renovated and maintained. The term ‘major renovation’ is used in the EPBD to describe renovations where more than 25% of the climate envelope is changed, or where the investment in the renovation is greater than 25% of the value of the building (European Parliament, 2010). Performing a major renovation does not necessarily imply that any changes are made in the building’s energy performance. Hence, the term ‘energy renovation’ has been used to describe building renovations that include EEMs implemented with the specific purpose of reducing the building’s energy demand. Femenías et al. (2018) identified that technical problems in buildings, such as water leakage or poor indoor environment, were the most common reason for initiating building renovations.

Other drivers for performing renovation include a desire to increase eco-friendliness, achieve energy savings or enhance building aesthetics (Jensen et al., 2018). A major renovation has a considerable effect on a building and the people who use it. Authors have highlighted benefits such as increased value of the building (Popescu, Bienert, Schützenhofer, & Boazu, 2012) and increased pride (Almeida & Ferreira, 2017).

Renovations have a long-term impact on the overall energy performance of the building stock. It is therefore important that the energy performance of the building is improved when buildings are renovated. Almeida and Ferreira (2017) discusses that relying on good energy performance of new buildings is insufficient for achieving overall objectives on energy efficiency improvement in the building stock. Large-scale building energy renovation is essential for reducing the climate impact from the building sector (Almeida & Ferreira, 2018). Reducing heat losses from buildings is one of the main ways to improve energy efficiency in the building sector, especially in cold climates. UN Environment and the International Energy Agency have estimated that around 39% of the equivalent CO₂ emissions from the building sector relate to heating or cooling demand dependent on the building envelope (UN Environment and International Energy Agency, 2017).

Common EEMs that reduce heat losses in a building include thermal insulation of the building envelope and installing heat recovery ventilation systems (Dodoo, Gustavsson, & Tettey, 2017; Galvin, 2010; Galvin & Sunikka-Blank, 2013; Lechtenböhmer & Schüring, 2011; Liu, Moshfegh, Akander, & Cehlin, 2014; Morelli et al., 2012; Thomsen et al., 2016; Truong, Dodoo, & Gustavsson, 2014). Several studies have demonstrated that it is possible to convert multi-family buildings into low-energy buildings or even to passive-house standard and nearly-zero energy buildings by ambitious energy renovation (Ferreira, Almeida, & Rodrigues, 2017; Friesen, Malbert, & Nolmark, 2012; Morelli et al., 2012; Wrålsen, O’Born, & Skaar, 2018). However, several authors have shown a gap between predicted energy use from energy renovation and actual use under building operation after energy renovation (Calì, Osterhage, Streblow, & Müller, 2016; Galvin, 2014; Majcen, Itard, & Visscher, 2016; van den Brom, Meijer, & Visscher, 2019). This is commonly referred to as the energy-efficiency gap (Jaffe & Stavins, 1994). Post-occupancy evaluation is essential for understanding building energy use and the effects from energy renovation.

Many housing companies have a goal of reducing energy use within the organization and when buildings are renovated. Femenías et al. (2018) showed that although many rental housing companies have energy savings targets, values other than energy efficiency often received more attention in practice. The same has been concluded by Reindl (2017) and Palm and Reindl (2018). Reindl (2017) showed that although energy efficiency was perceived as the second most important aspect in three studied

renovation projects, it did not receive much attention in the planning phase and EEMs were restricted by investment groups making financial decisions in the renovation. The implemented EEMs were decided based on previous experience in other renovation projects, and were not specific to the conditions in the existing building. Palm and Reindl (2018) studied barriers to improving energy efficiency through energy renovation and found that a lack of a common, clear energy saving goal was an important barrier. Studies have also shown a degree of skepticism towards energy efficiency or sustainable technologies in buildings (Dadzie, Runeson, Ding, & Bondinuba, 2018).

Costs have been identified as an important driver in the renovation context (Femenías et al., 2018; Jensen et al., 2018), and the cost-effectiveness of energy renovation is considered in several studies (Bonakdar, Dodoo, & Gustavsson, 2014; Dodoo et al., 2017; Galvin & Sunikka-Blank, 2013; Liu, Rohdin, & Moshfegh, 2016; Milić, Ekelöw, & Moshfegh, 2017). Focusing on the life cycle cost to identify cost-effective approaches in a renovation context has been suggested in several studies of the cost-effectiveness of energy renovations (Almeida & Ferreira, 2017; Ekström, Bernardo, & Blomsterberg, 2018) or in energy renovations with a limited budget (Sharif & Hammad, 2019). The Swedish National Board of Housing, Building and Planning studied whether it is cost-effective to achieve the minimum energy performance requirement for newly constructed buildings in two multi-family buildings (Swedish National Board of Housing Building and Planning, 2018a). They found that the requirement is not reached by implementing the EEMs identified as being profitable in previous energy audits of multi-family buildings. However, they highlight that the cost-effectiveness of EEMs is dependent on preexisting conditions in the building. This is in line with findings by Mørck et al. (2016) who argues that there is no one single approach that suites all buildings, and that it is important to consider differences in construction as well as local conditions and policies.

3.2.2 Demolition and constructing new buildings

Since many older buildings are energy inefficient, the investment needed to reduce energy use can be significant. There is also a limit to the level of energy reduction that can be achieved and still be within the limit of a cost-effective energy renovation (Almeida & Ferreira, 2017). Physical barriers to the adoption of EEMs could also exist in older buildings, for example difficulties installing air ducts, involving additional costs and a more complex renovation (Dadzie et al., 2018). Newer buildings generally have better energy performance compared to old buildings. An alternative approach to reduce energy use in the building sector overall could be to demolish buildings with poor energy performance and construct new buildings with modern energy performance. Power (2008) argues that renovation contributes more value to the community compared to demolition and constructing new buildings,

such as less disruption during the construction phase and more affordable housing. However, Bullen and Love (2010, 2011) showed through interview studies that one driver for demolishing a building rather than carrying out renovation is that the building does not meet the needs of the occupants or users and is thus perceived as no longer being viable. Demolition was generally considered when adapting the existing building structure to meet new needs was perceived to be too complicated compared to constructing a new building that meets these needs. Dadzie et al. (2018) showed in an interview study that demolition and constructing a new building was perceived to bring more benefits than performing extensive energy renovations. Some, but not all, of the respondents also perceived the cost of demolition and new construction to be lower than energy renovation for old buildings. Other values that are important in the choice between renovation and new construction are also highlighted, such as living comfort, noise levels, and indoor air quality (Morelli, Harrestrup, & Svendsen, 2014). However, many older buildings have historic values which means that they should not be demolished and the choice between renovation and demolition is thus complicated.

Several studies approach the choice between renovation and demolition and constructing a new building by analyzing embodied energy in the construction or the environmental impact from the two options (Ferreira, Duarte Pinheiro, & De Brito, 2015; Itard & Klunder, 2007; Marique & Rossi, 2018; Power, 2008, 2010; Verbeeck & Cornelis, 2011; Weiler, Harter, & Eicker, 2017). Few attempts to analyze the cost of energy renovation and compare the results with new construction have been identified. Morelli et al. (2014) show that renovation is a more cost-effective approach for Danish buildings dating from 1850-1930, and that since energy costs are small compared to other costs related to a new construction, improved energy efficiency is not able to compensate for the cost of new construction.

4 Case description

This section describes a building that has been used as a case study in paper I-IV and the typical building types used in Paper V.

The building used as a case study in the included papers is located in central Linköping, Sweden. It was constructed in 1961 and renovated in 2014. It had a lightweight concrete construction and an exhaust air ventilation system prior to energy renovation. The building is connected to Linköping's district heating network. The building before and after renovation can be seen in Figure 12. The building is partly shaded by vegetation and is relatively sheltered from wind by other buildings, see Figure 13.

Figure 12. The studied building before renovation (left) and after renovation (right).

Figure 13. Overview of building location (Used with permission from Linköping municipality).

The building has twelve apartments of various sizes located on the top four floors. Around half the ground floor is rented and used as offices and meeting rooms. The total heated area⁶ is 1072.5 m² and the building has a total apartment area of 918.5 m². The apartment layout on the second floor, building orientation, façade and cross section of the building are shown in Figure 14 and Figure 15.

Figure 14. Apartment layout on the second floor of the building with the apartments marked.

Figure 15. Façade facing south (left) and cross section of building (right).

⁶ Internal floor area of the building heated to more than 10°C.

The building had an average U -value of $0.54 \text{ W/m}^2\cdot^\circ\text{C}$ prior to energy renovation. The windows were mostly older three-pane windows, with the exception of the bathrooms, where all windows were older two-pane windows. A description of the technical properties for the different construction parts before renovation is presented in Table 2.

Table 2. Description of the construction before renovation.

Building part	Area	Original construction	U -value ¹ ($\text{W/m}^2\cdot^\circ\text{C}$)
External walls	569.9 m ²	0.01 m plasterboard, 0.25 m lightweight concrete, Cladding	0.43
Windows	106.9 m ²	Three-pane	1.9 ²
Bathroom windows	5.9 m ²	Two-pane	2.9 ²
Floor	216.5 m ²	0.2 m concrete, 0.1 m insulation Ground ⁴	0.2
Ceiling towards roof	23.1 m ²	0.15 m concrete, 0.04 m cork Roofing tile	0.91
Ceiling towards attic	194.5 m ²	0.05 m concrete, 0.12 m mineral wool, 0.2 m concrete	0.27
Total	1116.8 m ²		0.54

¹ U -values calculated in accordance with ISO 6946 - Building components and building elements - Thermal resistance and thermal transmittance (International Standard ISO 6946:2007). Values for thermal conductivity: lightweight concrete $0.12 \text{ W/m}\cdot^\circ\text{C}$, mineral wool $0.036 \text{ W/m}\cdot^\circ\text{C}$, cladding $0.8 \text{ W/m}\cdot^\circ\text{C}$, concrete $1.7 \text{ W/m}\cdot^\circ\text{C}$, cork $0.05 \text{ W/m}\cdot^\circ\text{C}$
² Standard glazing U -values for windows (IDA ICE version 4.8)
³ Information from manufacturer
⁴ Ground properties and floor U -value calculated in accordance with ISO 13370 - Thermal performance of buildings - Heat transfer via the ground - Calculation methods (International Standard ISO 13370:2007)

The windows were worn and in need of replacement. The façade had problems due to damage and discoloration from moisture, primarily on the backside of the building, as can be seen in Figure 12. The apartments were also worn and the entire building was in need of interior renovation. When the building underwent renovation in 2014, the façade was insulated with 100 mm mineral wool and the attic was insulated with 180 mm mineral wool. Due to the construction of the roof, it was not possible to insulate the façade with more than 100 mm insulation without rebuilding the roof. All windows were replaced with new three-pane low emissivity windows with a glazing U -value of $1.1 \text{ W/m}^2\cdot^\circ\text{C}$. The exhaust air ventilation system was replaced with a balanced mechanical ventilation system with a cross-flow plate heat exchanger. A storage area was also refurbished to a laundry facility during the

renovation, which the building did not have before it was renovated. As can be seen in Figure 15, some of the top floor apartments face the roof and some face the attic. It was not possible to insulate the roof, but the cork insulation in the roof was replaced with mineral wool with lower heat conductivity. The average U -value was reduced to $0.29 \text{ W/m}^2\cdot^\circ\text{C}$ as a result of the insulation and replacing the windows. The construction after the renovation can be seen in Table 3. The energy efficiency measures implemented by the housing company as part of the renovation were the common measures that are usually implemented as part of renovations with an energy focus.

Table 3. Construction after renovation.

Building part	Area	Renovated construction	U -value ¹ ($\text{W/m}^2\cdot^\circ\text{C}$)
External walls	569.9 m ²	0.01 m plasterboard 0.25 m lightweight concrete, 0.1 m mineral wool, Cladding	0.2
Windows	112.8 m ²	Three-pane (low emissivity)	1.1 ²
Floor	216.5 m ²	0.2 m concrete, 0.1 m insulation Ground ⁴	0.2
Ceiling towards roof	23.1 m ²	0.15 m concrete, 0.04 m mineral wool Roofing tile	0.71
Ceiling towards attic	194.5 m ²	0.05 m concrete, 0.3 m mineral wool, 0.2 m concrete	0.12
Total	1116.8 m ²		0.29

¹ U -values calculated in accordance with ISO 6946 - Building components and building elements - Thermal resistance and thermal transmittance (International Standard ISO 6946:2007). Values for thermal conductivity: lightweight concrete $0.12 \text{ W/m}\cdot^\circ\text{C}$, mineral wool $0.036 \text{ W/m}\cdot^\circ\text{C}$, cladding $0.8 \text{ W/m}\cdot^\circ\text{C}$, concrete $1.7 \text{ W/m}\cdot^\circ\text{C}$, cork $0.05 \text{ W/m}\cdot^\circ\text{C}$
² Standard glazing U -values for windows (IDA ICE version 4.8)
³ Information from manufacturer
⁴ Ground properties and floor U -value calculated in accordance with ISO 13370 - Thermal performance of buildings - Heat transfer via the ground - Calculation methods (International Standard ISO 13370:2007)

A summary of building characteristics, climate and geographical information that are central to understand the energy demand in the building can be seen in Table 4.

Table 4. Information about building location and characteristics of the building before and after renovation.

Other information		
Location (coordinates)	58.41; 15.61	
Winter design dry bulb temperature	-17.6°C (ASHRAE, 2016)	
Summer design dry bulb temperature	27.3°C (ASHRAE, 2016)	
	Before renovation	After renovation
Heated floor area	1072.5 m ²	1072.5 m ²
Space heating demand	96.3 kWh/m ² ·year	52.9 kWh/m ² ·year
Average indoor temperature during winter ¹	19.5-19.8°C	21-21.2°C
Central heating system	District heating	District heating
Room heating system (supply/return temperature)	Radiator (80/60°C)	Radiator (60/40°C) AHU heating coil
Ventilation system	Exhaust system	Supply and exhaust system
Ventilation air change rate	0.82 h ⁻¹	0.79 h ⁻¹
Heat recovery	-	57.4% ⁵
Building envelope permeability at -50Pa ² (q ₅₀)	0.35 l/s·m ²	0.49 l/s·m ²
Windows solar gain factor (g-value)	0.68	0.43
Assumed losses from thermal bridges (based on “typical” loss factors in IDA ICE)	43.2 W/K	42.9 W/K

¹ Measured in occupied apartment during heating season before and after renovation.

² Measured with blower door method.

4.1 Typical building constructions

Between the years 1961 and 1975 Sweden had a record breaking period of new building construction and nearly 1.4 million new buildings were constructed (Johansson, 2012; Swedish National Board of Housing Building and Planning, 2003). The period is commonly referred to as the Swedish record years. The studied building represent a common building construction type from the record years. In addition to the studied building, Paper V includes a comparison of renovating building types that were common in Sweden in the 1940s, 1950s, and 1970s. The studied building is used as reference for the 1960s building and all four buildings were assumed to have the same external geometry. The two oldest buildings were assumed to have a higher ceiling height, which was common in buildings from this

time, and thus have one less floor compared to the two newer building types. The difference in wall thickness means that the buildings have different internal measurements and different heated areas as well as apartment areas. The building constructions and characteristics are summarized in Table 5. Apartment areas, U -values and areas of individual building parts are detailed in Paper V. The ventilation rate is the minimal requirement in the Swedish Building Code.

Table 5. Construction and characteristics of the analyzed building types.

Year	Wall construction	Heated area (m ²)	Window type	Ventilation system	Average U -value (W/m ² ·°C)	Space heating demand (kWh/m ² ·year)
1940	1½ brick wall	804.7	Two-pane	Natural	0.94	188.0
1950	Insulated brick wall	834.6	Two-pane	Natural	0.79	157.0
1960	Lightweight concrete	1072.5	Three-pane	Exhaust	0.51	113.5
1970	Insulated concrete cavity wall with external brick	1032.9	Three-pane	Exhaust	0.50	116.2

5 Research design and methodological approach

This sections describes the methodological approaches used in the included papers. A combination of field measurements, whole building energy simulations, questionnaires, life cycle cost analysis and optimization has been used.

The research and the papers written during the research process have been divided into three main parts, which have also guided the choice of research questions.

- 1) Analysis of energy use and indoor environment in a building prior to and after energy renovation using field measurements, dynamic building energy simulations and questionnaires.
- 2) Analysis and evaluation of the performed energy renovation with regard to life cycle cost (LCC) and identification of LCC optimal energy renovation of the studied building and other building types.
- 3) Analysis of alternatives to energy renovation of different building types by demolishing and constructing a new building from an LCC perspective.

The multi-family building presented in section 4 is used as a case study to gain an understanding of the effects of energy renovation and to study different approaches. The building stock in any country is a diverse collection of buildings of different sizes, constructions, uses and ages. Any attempt to make a generalized prediction of the energy saving potential in a building stock will include uncertainty factors due the heterogeneity of buildings, including those constructed during the same era. In contrast to a statistical approach that relies on a large sample size, case study methodology often includes multiple sources of evidence with many variables, methods, tools and data collection approaches (Yin, 2014). Although this means that case studies are unable to give a statistical generalization of a phenomenon, they do offer the possibility to gain a deep analytical understanding and to make analytical generalizations about the findings from the case.

The approach in the research presented here builds on several methodological approaches. During all phases, validation of the results has been a central part of the research. In Papers I-II, empirical validation of dynamic BES was performed using field measurements from a reference apartment in the studied building and energy use at building level. The results from Paper III are based on a questionnaire on perceptions of the indoor environment, and the empirically validated BES model

was used to validate the results from the questionnaire. In Paper IV, the accuracy of predicted space heating demand with a quasi-steady state heat balance calculation included in the LCC optimization was validated using the validated BES model. An overview of the methodological approaches used in the different papers can be seen in Table 6.

Table 6. Methodological approaches in the included papers.

	Paper I	Paper II	Paper III	Paper IV	Paper V
Measurements	×	×			
BES modelling	×	×	×	×	
Questionnaire on indoor environment			×		
LCC optimization and analysis				×	×
Validation	×	×	×	×	
Primary energy use		×			

Paper II analyses primary energy use and climate impact before and after the energy renovation. In this thesis, an analysis is also performed on the primary energy use after implementing the energy efficiency measures (EEMs) that are found cost-optimal for the studied building presented in Paper IV. The Swedish Building Code is used as a basis for the analysis and discussion.

5.1 Field measurements and evaluation of the renovated building

Extensive field measurements were performed to evaluate the effects of the energy renovation. Table 7 shows the data collected from field measurements and a questionnaire to evaluate the effect on space heating demand, indoor environment and thermal comfort. Most of the data was used as input data in the BES model. All measurements were carried out both before and after the energy renovation, except for measuring the heat recovery efficiency of the new ventilation unit which was installed as part the energy renovation. A summary of measurement equipment and its accuracy can be found in Paper II.

Table 7. Data collection in the building from field measurements and questionnaire.

	Level		Renovation status		Use of data		
	Apartment	Building	Before	After	Model input data	Model validation	Other use of data
Room air temperature	×		×	×	×	×	
CO ₂ in room air	×		×	×	×		
Household electricity use	×		×		×		
Air tightness	×		×	×	×		
Thermal camera	×		×	×			× ¹
Ventilation heat recovery efficiency		×		×	×		
Outdoor air temperature		×	×	×	×		
Outdoor relative humidity		×	×	×	×		
Wind speed and direction		×	×	×	×		
Questionnaire on perceived indoor environment	×		×	×			× ²

¹ A thermal camera was used to identify potential air leakages in the building envelope during depressurizations of the reference apartment.

² The responses from the questionnaire supplemented the indoor thermal environment simulations, and were used to analyze the effect on the indoor environment of the energy renovation.

Table 8 shows external data sources used in the BES model, primarily as input data. The district heating used for space heating purposes was measured on a monthly basis by the property owner and used to validate the accuracy of the model in predicting monthly space heating demand.

Table 8. External data used in the dynamic whole building energy simulation model.

	Renovation status		Use of data			Data collection
	Before	After	Model input data	Model validation	Other use of data	Data source
District heating use for space heating	×	×		×		Property owner
Construction blueprints	×	×	×			Property owner
Household electricity use		×	×			Electricity grid provider
Ventilation certificates	×	×	×			Property owner
Outdoor air temperature	×	×	×			SMHI ¹
Outdoor relative humidity	×	×	×			SMHI ¹
Wind speed and direction	×	×	×			SMHI ¹
Solar radiation	×	×	×			STRÅNG ²

The main field measurement data collection took place between 2013 and 2015. An overview of when the measurements took place can be seen in Figure 16.

Figure 16. Timeline of field measurements and data collection.

Two reference apartment was used for measurements at apartment level. Since the resident in the apartment used as a reference prior to renovation had moved out and the new residents were not interested in their apartment being used for reference measurements, another apartment was used. The apartment was of a similar size and was located in the same part of the building one floor down, see Figure 17.

Figure 17. Location and apartment layout of the reference apartments used before renovation (red) and after renovation (blue). Locations of air temperature measurements are indicated with stars.

5.1.1 Airtightness

The airtightness of the building envelope was measured in the building prior to and after the renovation. The same apartment was used (the apartment used as a reference in the renovated building, which was vacant prior to the renovation). The measurements were performed using the Blower Door method. When the airtightness of the building envelope is measured using the blower door method,

ventilation inlets/outlets and other openings, such as drains, are covered so that air leakages through gaps, cracks or holes where undesired air leakage occur can be measured (International Standard ISO 9972-2015, 2015). A pressurization and depressurization of 50 Pascals is then induced using a high power fan, and the air flow needed to induce the pressure is noted to indicate the airtightness of the building. An alternative to the blower door method for pressurization is to use the air-handling unit in the building, which has been shown to work well in buildings where it is not possible to follow standardized methods (Jeong, Firrantello, Bahnfleth, Freihaut, & Musser, 2008).

The pressure induced in the building during the measurement is much greater than the pressure induced by wind pressure or temperature difference. By studying a large number of dwellings, the infiltration at normal pressure was approximated to around 1/20 of the air exchange measured at a pressure difference of ± 50 Pascals (Awbi, 2003). The measurement of leakage under pressurization can be used to compare the airtightness of different buildings. In Sweden, the air leakage per enclosing area at a pressurization of ± 50 Pascals, q_{50} ($\text{l/s}\cdot\text{m}^2$), is commonly used. A thermal camera was used to identify significant leakage of air when the building was under depressurization. Since the outdoor temperature was lower than the indoor temperature, a thermal camera was able to identify leakage of cold air.

5.1.2 Ventilation heat recovery efficiency

When the building was renovated, a plate heat exchanger was installed. The temperature efficiency of the heat exchanger was measured during one month of operation (from December 9, 2015 to January 13, 2016). Temperature loggers were placed in the ventilation ducts for supply (T_{supply}), return (T_{return}) and exhaust air (T_{exhaust}), as well as after the heat exchanger (T_1). An overview of the air handling unit with arrows indicating where temperature was measured can be seen in Figure 18. A surface temperature meter was placed on the heating coil to indicate whether or not it was operating. Temperatures were logged at an interval of three minutes.

Figure 18. Overview of air handling unit in the studied building, with locations where temperature was measured indicated with arrows.

There was only a limited amount of ventilation duct between the heat exchanger and the heating coil where air temperature could be measured. The results from the air temperature measurements after the heat exchanger (T_1) appeared to be affected by the operation of the heating coil and hence the heat exchanger efficiency, η , was calculated using the temperature drop of the exhaust air over the heat exchanger, in accordance with Equation 9.

$$\eta = \frac{T_{\text{return}} - T_{\text{exhaust}}}{T_{\text{return}} - T_{\text{out}}} \times \frac{q_{\text{supply}}}{q_{\text{exhaust}}} \quad [9]$$

where q_{supply} is the supply air flow (m³/s), and q_{exhaust} is the exhaust airflow. The airflow was balanced at the time of the measurements.

5.2 Whole building energy simulation

Different approaches to predicting energy use in buildings offer different levels of detail and require different amounts of data, time and effort. Regardless of the approach taken, calculating or modelling energy use will represent a simplified version of reality (De Wilde, 2018) and will include some degree of uncertainty. A building's energy use can be calculated using heat losses and degree-hours with the approaches presented in section 2.2. Although this offers a relatively accurate prediction of annual heat demand, it does not give an estimate of the conditions in the building and is based on simplified user behavior and internal heat gains (IHG) from people, appliances and solar radiation. BES offers a detailed prediction of building energy use, thermal climate within the building, and heating, ventilation and air conditioning systems. In contrast to a static or quasi-steady state calculation of building heat demand, a dynamic approach offers the possibility to study heat demand and indoor climate with a high level of detail at zone or room level. However, this requires more detailed information about the building and more input data. A BES model often includes data on the building's construction and usage (for example when occupants are present and the amount of electricity used in the building) (Ryan & Sanquist, 2012), and climate data from the building location is used to predict heat demand and indoor climate.

User behavior is usually one of the largest sources of uncertainties in simulation or calculation of building energy demand (Bonte, Thellier, & Lartigue, 2014; Hoes, Hensen, Loomans, de Vries, & Bourgeois, 2009; Widén, Molin, & Ellegård, 2012; Zhao, Lasternas, Lam, Yun, & Loftness, 2014). Dar et al. identify three main factors that will influence heat gains from occupants: occupant behavior, appliance use and family size (Dar, Georges, Sartori, & Novakovic, 2015). They show that differences in behavior, e.g. time spent at home, and family size can explain the gap between predicated and actual energy use in building to a large extent. The influence from user behavior in the buildings has been studied in a sensitivity analysis in Paper II.

IDA Indoor Climate and Energy (IDA ICE) has been used in the papers included in the thesis for dynamic BES.

5.2.1 The model

The model was created in IDA ICE version 4.6. The dynamic simulations presented in the papers were performed using different versions of IDA ICE: Papers I-II in IDA ICE 4.6, Paper III in version 4.7 and Paper IV in version 4.8

The BES model was constructed from blueprints of the building. Each apartment was modelled as one zone, except for the reference apartments where each room was modelled as one zone to allow for validation at room level. Ventilation air flow was based on ventilation certificates. Objects that shaded the building were based on city maps and estimations of the heights of surrounding buildings. The building was assumed to be relatively sheltered from wind exposure due to its location in the city center. The typical loss factors for thermal bridges in IDA ICE version 4.6 were assumed for the building.

Climate data for the whole year energy simulation was collected from the Swedish Hydrological and Meteorological institute (SMHI). The nearest measuring location was used (Malmslätt), which is around 5 kilometers west by southwest of the building. SMHI measures temperature, relative humidity, wind direction and wind speed at one hour intervals. The STRÅNG solar radiation model developed by SMHI was used to collect hourly modelled data on direct and global radiation at the building location (Swedish hydrological and meteorological institute, n.d.). A simplified version of the Reindl model was used to calculate the hourly diffuse fraction of the global radiation (Reindl, Beckman, & Duffie, 1990).

5.2.2 Validation of BES model results

Prediction accuracy is the main objective in all BES approaches, and validation is central in order to ensure that the results are valid and represent the reality in a satisfactory manner (Coakley, Raftery, & Keane, 2014; De Wilde, 2014; Jensen, 1995; Rohdin, Dalewski, & Moshfegh, 2012). In contrast to BES model calibration, where the model parameters are adjusted and tuned to fit observed conditions (Reddy, 2006; Reddy, Maor, & Panjapornpon, 2007), validation of BES model results means that the accuracy in the output from the model is tested against something that is known or measured. Several approaches for BES model validation are commonly used (Coakley et al., 2014; Jensen, 1995; Ryan & Sanquist, 2012; Witte, Henninger, & Glazer, 2001):

- 1) Analytical validation, where the results from the model are compared with a known calculated solution.
- 2) Peer model validation, where the results from several different models using the same input data are compared against each other.
- 3) Empirical validation, where the results from a simulation are compared to measurements obtained in test cells (idealized empirical validation) or measurements in an operational building (realistic empirical validation).

Empirical validation is often seen as the most comprehensive approach for validating BES model results. However, Coakley et al. (2014) emphasize that, in addition to ensuring that a BES model is accurate at predicting the heat demand, it should also be able to predict the simulated environment with a high degree of accuracy.

IDA ICE, which has been used for simulation in the papers included in this thesis, has been validated in accordance with ASHRAE Standard 140-2004 (Equa Simulation AB, 2010a), CEN Standards EN 15255-2007 and 15265-2007 (Equa Simulation AB, 2010b), CEN Standard EN 13791 (Kropf & Zweifel, 2001) and IEA's SHC Task 34 (Loutzenhiser, Manz, & Maxwell, 2007).

The empirical validation was performed at two levels: room level and building level. At room level, the model's ability to predict the indoor temperature was analyzed during summer and winter before renovation, and during winter after renovation. User behavior is central at room level, and detailed user patterns were created from the measurements in the reference apartments. The simulation was performed for the entire building, and time schedules with a one hour time step were used for equipment and the presence of occupants in the reference apartment based on the measurements. A climate file was created with climate data collected at the building location. The variance, σ^2 , between measured and modelled temperature at room level was calculated using Equation 10.

$$\sigma^2 = \frac{\sum (X_{measured} - X_{modelled})^2}{N} \quad [10]$$

where $X_{measured}$ is the measured indoor air temperature, $X_{modelled}$ is the modelled temperature at the same time, and N is the number of measurements during the validation period. The standard deviation, σ , was calculated as the square root of the variance. The indoor temperature was measured at five minute intervals. The output data from the simulations had the same interval as the measurements. A parametric simulation with twelve calculation phases was performed, starting two weeks before the validation period and ending two weeks after.

When the accuracy in predicting the environment at room level been tested and assured, a validation took place at building level with regard to the model's ability to

predict the monthly space heating demand. Standard values from the SVEBY program (Sveby, 2012) were used for IHG from appliances and occupancy presence.

5.2.3 Simulation of thermal comfort

The validated BES model was used to simulate thermal comfort in the building prior to and after energy renovation. Thermal comfort was calculated during a year with normal year corrected climate data from Linköping (ASHRAE, 2016). IDA ICE calculates Fanger's comfort indices (Predicted Mean Vote and Predicted Percentage Dissatisfied) in accordance with international standard ISO 7730:2005 (International Standard ISO 7730:2005, 2005). Thermal comfort was simulated for an occupant situated one meter from the largest window in accordance with recommendations from the Sweden Green Building Council (Sweden Green Building Council, 2014). This is considered to be the most exposed location in a building, and should be used to simulate thermal comfort during both summer and winter. The occupant had clothing with a thermal resistance of $0.13 \text{ m}^2 \cdot ^\circ\text{C}/\text{W}$ (corresponding to 0.85 clo), but was able to adjust the clothing value by $\pm 0.04 \text{ m}^2 \cdot ^\circ\text{C}/\text{W}$ (0.25 clo). The model had no adaptive solar shading or airing when the indoor temperature is high. Four different apartments was analyzed: two small apartments on the second and fifth floors and two large apartments on the same floors, see Figure 19.

Figure 19. Zones used for simulation of thermal comfort before and after renovation. The location of the occupant for simulated comfort index is marked with a star.

5.3 Primary energy use

Paper II uses primary energy factors (PE factors) to analyze the effect from energy renovation with regard to the primary energy use. Paper V uses the PE factors from the Swedish Building Code to identify suitable EEMs for renovating to the same level of energy performance as a newly constructed building. The Swedish Building Code allows a maximum energy performance of 85 kWh/m²·year (primary energy). In this thesis, the analysis has been expanded with PE factors from three different district heating systems, the average for all Swedish district heating systems, and the PE factor of 2.1 for electricity suggested by the Swedish Environmental Institute (Gode, Martinsson, Hagberg, & Palm, 2011; Martinsson, Gode, Arnell, & Höglund, 2012). The factors are used to analyze the combinations of EEMs suitable for achieving the different energy savings targets presented in Paper IV. A comparison is made with the PE factor used in the Swedish Building Code where all energy carriers are assigned a PE factor of 1, except electricity which has a PE factor of 1.6 (Swedish National Board of Housing Building and Planning, 2018b). The heat demand is also corrected for the climate in the building location in accordance with the building code, which in the case of Linköping means a correction factor of 1.

For the analysis in this thesis, one system with a small impact and one system with a large impact in terms of PE factor and greenhouse gas emissions was used in addition to the system in Linköping. The district heating system in Linköping has low resource use and a low PE factor (0.09). However, since it is based on combustion, it has a relatively high climate impact compared to other Swedish district heating systems (101 gram CO₂eq⁷/kWh). The system used as a district heating system with low impact is the system in Enköping, which uses renewable fuels and waste heat, meaning that both primary energy use (0.06) and emissions are small (5 g/kWh). For a system with high impact, Uppsala was used⁸. The district heating in Uppsala is produced from the combustion of peat and waste and thus has a relatively high primary energy use (0.54) and greenhouse gas emissions (194 g/kWh). The average district heating network in Sweden has equivalent CO₂ emissions of 57.5 g/kWh and a PE factor of 0.16. A summary of the systems can be seen in Table 9.

⁷ Equivalent CO₂ emissions that take consideration to different global warmings potential of difference greenhouse gases.

⁸ The system in Uppsala was chosen after discussions with Energiföretagen. Note that the system is not the system with the highest primary energy use and greenhouse gas emission in Sweden. However, it represents one of the larger district heating networks in Sweden with high resource intensity and climate impact, according to Energiföretagen. Also note that peat is being phased out from the system and the primary energy use and emission from the system will decrease as a result of this.

Table 9. Description of the district heating systems included in the analysis of primary energy use from the renovation approaches presented in Paper IV.

System	Description of system	PE factor	Reference
Linköping	Based on combined heat and power using waste	0.09	(Energiföretagen, 2017)
Low impact system (Enköping)	Based on renewable fuel and waste heat	0.06	(Energiföretagen, 2017)
High impact system (Uppsala)	Combustion primarily of peat and waste	0.54	(Energiföretagen, 2017)
Average Swedish district heating	-	0.16	(Energiföretagen, 2017)
Swedish Building Code	-	1.0	(Swedish National Board of Housing Building and Planning, 2018b)

Standards values for domestic hot water (DHW) have been included in the analysis as well as annual electricity demand for building purposes from the actual building. A ground source heat pump is included as an alternative heat supply system. A total of seven different system boundaries are thus included in the analysis. A summary of the PE factors used is shown in Table 10.

Table 10. PE factors used for the analysis of primary energy use from different system boundaries and approaches to include primary energy use from building energy use.

	Space heating	Domestic hot water	Building electricity
District heating, Linköping	0.09	0.09	2.1
District heating, low impact	0.06	0.06	2.1
District heating, high impact	0.54	0.54	2.1
District heating, average	0.16	0.16	2.1
District heating, building code	1	1	1.6
Heat pump, Swedish average	2.1	2.1	2.1
Heat pump, building code	1.6	1.6	1.6

5.4 Questionnaire on perceived indoor environment

A standardized questionnaire investigating perceptions of the indoor environment in residential buildings was used in Paper III. The questionnaire was developed by the Department of Occupational and Environmental Medicine at Örebro University Hospital in Sweden in 1988 (Andersson, Stridh, Fagerlund, & Larsson, 1993). The questionnaire is divided into two parts, one focusing on how the respondent perceives the indoor environment, and one focusing on different symptoms of poor indoor environment experienced by the respondent and whether he or she thinks these are related to the indoor environment. The questions regarding the indoor environment are in turn divided up into the indoor thermal environment and how the respondent perceives the indoor temperature, indoor air quality, and how the respondent perceives noise levels in the apartment or house. An overview of all the aspects considered in the questionnaire are found in Paper III, and a summary of the aspects relating to the thermal environment discussed in this thesis can be seen in Table 11. The questionnaire has been used in studies addressing the indoor environment in both new and renovated buildings (Andersson, Fagerlund, Bodin, & Ydreborg, 1988; Liu et al., 2015; Liu & Thoresson, 2013; Rohdin et al., 2012; Rohdin, Molin, & Moshfegh, 2014).

Table 11. Problems relating to a poor thermal comfort included in the questionnaire. (For problems relating to indoor air quality and noise, see Paper III.)

Experienced problems related to the thermal environment
Draught ¹ ; low room temperatures ¹ ; high room temperatures ¹ /too warm during summer ^{2,3} ; varying room temperatures ¹ ; temperature varies with outdoor temperature; cold floors during winter ² ; unable to affect indoor temperature ²
¹ Possible answers: “No, never”, “Yes, sometimes”, “Yes, often” ² Possible answers: “No”, “Yes” ³ Both checked in same questionnaire counted as one answer

The questionnaire was handed out to all twelve households in the building in October 2013, before the building was renovated, and in February 2015, five months after the energy renovation had been completed. The residents were given a letter describing how the questionnaire would be used. Seven out of the twelve households responded prior to renovation, and six households responded after the renovation. Many of the responding households were new to the building after the renovation, but all respondents before the renovation had lived there for more than one year when they answered the questionnaire.

5.5 Life cycle cost optimization and calculation

Achieving the objective of a system while using minimal resources or at minimal costs is often desirable (Churchman, 1968). The cost-effectiveness of EEMs in energy renovation will vary from building to building depending on thermal performance, ventilation system and use. When considering buildings, the time perspective must also be considered in relation to cost-effectiveness. The long life cycle of buildings means that many authors have suggested LCC approaches for studying whether or not it is cost-effective to implement EEMs as part of building renovations (Brown, Malmqvist, Bai, & Molinari, 2013; Liu et al., 2016; Milić et al., 2017; Spickova & Myskova, 2015). LCC analysis is an approach that summarizes the costs occurring during a building's life cycle, discounted to present costs (Gluch & Baumann, 2004). Several studies have used approaches that include cost optimization in a renovation or building context (Almeida & Ferreira, 2018; Bonakdar et al., 2014; Ferreira, Almeida, & Rodrigues, 2016; Ferreira, Almeida, Rodrigues, & Silva, 2016; Ganiç Sa, Zerrin Yilmaz, Becchio, & Corgnati, 2017; Gustafsson, 1990, 1988; Hamdy, Hasan, & Siren, 2013; Mauro, Hamdy, Vanoli, Bianco, & Hensen, 2015; Milić et al., 2017; Oliveira, Figueiredo, Vicente, & Almeida, 2018). LCC optimization is included in several of these studies.

Both building renovation and the construction of new buildings include many measures and installations that have no effect on the building's energy use. The LCC optimization performed in Papers IV-V includes parts of the building body that influence energy use: insulation of the building envelope, window replacement and ventilation measures, as well as the heating system installed to cover the building heat losses and the heating costs during the selected life cycle.

Achieving the lowest LCC (LLCC) for the renovated building means that the energy renovation is optimized solely in terms of cost during the life cycle. Depending on the cost of energy and EEMs, and on the thermal performance of the building prior to renovation, the level of EEMs that it is suitable to implement will vary. If the building has a high level of energy performance prior to renovation and has a heating system with low operation costs, it is likely that it will not be cost-effective to implement any EEMs to achieve the LLCC. In addition to the LLCC for the building, the cost-optimal LCC for achieving a reduction in heat demand ranging between 10% and 70% of the original energy use has been identified for the buildings included in Papers IV-V.

5.5.1 Life cycle costs of renovated building

The approach to calculating the LCC of building renovation was described by Gustafsson (1988, 1990). The total LCC, LCC_{total} , for the renovation is calculated using Equation 11.

$$LCC_{total} = LCC_{maintenance} + LCC_{HS} + LCC_{EEM} + LCC_{operation} - RV \quad [11]$$

where $LCC_{maintenance}$ is the discounted sum of the cost of maintaining the building in an acceptable condition (SEK), LCC_{HS} is the cost of installing a heating system with the required maximum thermal power (SEK), LCC_{EEM} is the cost of investment in EEMs implemented in the building to reduce space heating demand (SEK), $LCC_{operation}$ is the cost of operating the building (in this case supplying space heating) during the entire life cycle (SEK), and RV is the residual value for any investment that has a value after the life cycle (SEK).

All costs included in the total LCC that do not occur annually are discounted to present value, PV , using Equation 12.

$$PV = N \times (1 + r)^{-a} \quad [12]$$

where N is the non-annually occurring investment cost in maintenance, heating system or EEMs, r is the discount rate, and a is the number of years until the cost occurs. If the lifetime of the investment is shorter than the period for which the LCC is calculated, a new investment is made and included in the LCC.

Operation cost, in this case space heating, recurs on an annual basis. The present value for recurring costs are calculated using Equation 13.

$$PV = R \times \frac{1 - (1 + r)^{-b}}{r} \quad [13]$$

where R is the annually recurring cost of space heating the building, and b is the number of years that R occurs during the life cycle. The annual cost is based on a quasi-steady state heat balance calculation with twelve time steps based on the approach described in section 2.2. Thermal bridges was assumed to represent 10% of the total transmission losses in the building. A full description of the space heating demand calculation can be found in Papers IV and V.

5.5.1.1 Life cycle cost optimization

The LCC optimization in Papers IV-V was performed using the optimization tool OPERA-MILP (OPTimal Energy Retrofit Advisory-Mixed Integer Linear Programming). The tool was developed to identify EEMs for reducing the LCC of buildings undergoing renovation, and calculates the LCC using Equation 8-10.

Several publications include studies of building renovation LCC optimizations based on OPERA-MILP (Gustafsson, 1998, 2000; Gustafsson, 2001; Liu et al., 2016; Liu, 2017; Milić et al., 2017).

OPERA-MILP includes EEMs that reduce the space heating demand (thermal insulation, window replacement and improving airtightness by weather stripping windows). The costs are divided up into inevitable costs of measures that must be performed in the building to maintain it at an acceptable standard and costs of EEMs that can be implemented to reduce space heating demand. The inevitable maintenance measures and EEMs are summarized in Table 12.. In Papers IV-V, the cost function for window weather stripping was used to include the cost of installing a new ventilation system with heat recovery (HRX system).

Table 12. Inevitable maintenance and EEMs of different building parts (Papers IV-V).

	Inevitable maintenance measures	Energy efficiency measures
Façade	Façade cleaning and repainting of light weight concrete structure, none for brick façades	Insulation with mineral wool, new façade plaster
Attic and roof	None	Insulation of attic with mineral wool
Windows	New wood framed windows with U -value of original window type	New aluminum framed windows with U -value 1.1 or 0.8 W/m ² ·°C
Ventilation system	None	Supply and exhaust air ventilation system with heat recovery

Linear cost functions are used to calculate the cost of insulation measures and installing a new heating system. The total cost of maintaining and, if applicable, adding thermal insulation to the building envelope, $C_{envelope}$, is calculated in Equation 14.

$$C_{envelope} = CE_1 + (CE_2 + CE_3 \times t) \quad [14]$$

where CE_1 is the inevitable maintenance cost of the specific part of the building envelope (SEK/m²), CE_2 is costs relating to insulating the envelope independent of the insulation thickness (SEK/m²), CE_3 is costs relating to insulating the envelope dependent on and linear to the insulation thickness (SEK/m²·m), and t is the thickness of the insulation (m). The cost of installing new windows is calculated in the same way, but includes no CE_3 cost. Instead, the costs of different windows with different U -values are included in the optimization. Since the four buildings types

included in Paper V have different constructions, the costs of maintenance and EEMs vary between the buildings.

The cost for installing a heating system is calculated in a similar way to insulation measures, see Equation 15.

$$C_{HS} = HS_1 + HS_2 \times P + HS_3 \times P \quad [15]$$

where HS_1 is the cost of installing a new heating system regardless of maximum power (SEK), HS_2 is the cost of installing a new heating system and is linear to the maximum power of the heating system (SEK/kW), P is the maximum power of the heating system (kW), and HS_3 is costs relating to systems needed in connection with the heating system, such as pipes, a chimney or a bore hole (SEK). The heating system (HS_1 and HS_2) and related systems (HS_3) can have different technical lifetimes.

The specific costs for maintenance and insulation of the building envelope in the different building types, window replacement and a district heating exchanger are presented in Paper V, and were based on costs from Wikells Sektiondata (Wikells Byggberäkningar AB, 2018).

5.5.2 Life cycle cost analysis of constructing a new building

The analysis performed in Paper V includes the demolition of four different building types representing common Swedish construction techniques from the 1940s, 1950s, 1960s and 1970s, as presented in Table 5. To be able to compare the cost of energy renovation with new construction, the same parts of the building body have been included in the LCC of the new construction. In addition to the costs presented in Table 12 and Paper IV, the comparison between energy renovation and demotion and new construction in Paper V includes renovation of the external roof of the four studied building types. The LCC of demolishing an old building and constructing a new building, $LCC_{new\ building}$, is calculated in Equation 16.

$$LCC_{new\ building} = C_{demolition} + LCC_{construction} + LCC_{HS} + LCC_{heating} - RV \quad [16]$$

where $C_{demolition}$ is the cost of demolishing the existing building (SEK), and $LCC_{construction}$ is the discounted sum of construction costs for the building body (SEK). The cost of the heating system and space heating are calculated in the same way as the LCC for the renovated building presented in Equation 11.

The new building included in the analysis is based on a model developed by the Swedish Association of Public Housing Companies (Swedish Association of Public Housing Companies, n.d.). The building has prefabricated sandwich wall elements, three-pane low emissivity windows and a balanced mechanical ventilation system

with heat recovery (see Paper V for specific construction and performance). The building has the same external geometry as the case study building, and has energy performance as defined by the Swedish Building Code of 84.9 kWh/m²·year (primary energy) including standard DHW use and electricity use for building purposes from the studied building. Demolition costs vary between the different building constructions and are higher for constructions with high mass, such as the buildings from the 1970s.

6 Results and discussion

The results are divided into three sections corresponding to the three research questions. Section 6.1 discusses the effects on a building in terms of space heating demand and indoor environment as a result of energy renovation (primarily based on results from Papers I-III), section 6.2 discusses life cycle cost-optimal strategies for energy renovation and primary energy use (primarily based on results from Papers II, IV and V), and section 6.3 discusses the choice between energy renovation and demolition and constructing a new building from the perspective of life cycle costs (primarily based on results from Papers IV and V).

6.1 Effects on energy use and indoor environment

Research question 1 - What is the measured and predicted space heating demand and perceived indoor environment before and after energy renovation, and how do the predicted results compare to the measured data?

Papers I and II focus on the effect on space heating demand as a result of the energy renovation of the studied building, primarily using building energy simulation (BES) modelling. The indoor temperature in the non-renovated and renovated building was predicted with a maximum standard deviation of 0.37°C in all zones except one, where the user behavior changed during the measurements. The annual heat demand was predicted with a difference of 3.7% compared to measured heat demand before the energy renovation. Paper I indicated a gap between the measured and modelled heat demand in the renovated building, with heat recovery efficiency and user behavior discussed as possible reasons. The efficiency of the heat recovery unit was therefore measured during one month of operation and was calculated at 57.4%, which is lower than expected. With the measured heat recovery efficiency, the annual heat demand was predicted with a difference of 5.6% compared to measured heat demand. The BES model was thus able to predict both a realistic simulated environment and heat demand.

The modelled heat demand during a year with normal climate data is 92.3 kWh/m²·year excluding domestic hot water (DHW) before the building was renovated. However, the indoor temperature in the reference apartment ranged between 19.5°C and 19.8°C, and was thus lower than national recommendations and what is common in Swedish multi-family buildings. Once the building had undergone renovation the indoor temperature in the reference apartment ranged between 21.0°C and 21.2°C during the winter. The normal year corrected heat demand was modelled to 51.6 kWh/m²·year after renovation, which means a

reduced heat demand of 44%. If the building had been heated to 21°C prior to renovation, the modelled heat demand is 99.6 kWh/m²·year and the energy efficiency measures (EEMs) implemented during the energy renovation therefore had a potential to reduce heat demand by 48%. The building’s heat balance before and after the energy renovation can be seen in Figure 20.

Figure 20. Heat balance for the building before renovation (top) and after renovation (bottom) (Paper II).

The transmission losses are reduced from all building parts that were thermally improved in the energy renovation, see Figure 20. The heat losses from the floor,

which was not changed in the renovation, have increased due to the higher indoor temperature. A smaller fraction of the internal heat gains (IHG) are useful, i.e. substitute space heating, when the heat losses are reduced and the balance temperature becomes lower. The new windows with a lower solar heat gain coefficient also mean that heat gains from solar radiation are decreased. However, as shown in Papers II, III and IV, installing a window type with a higher solar heat gain coefficient will decrease heat losses at the expense of problems with poor thermal comfort during the summer.

In addition to space heating demand, Paper II also analyzes the indoor environment prior to and after the renovation. Paper III includes dynamic simulation of the indoor thermal comfort and indicates that there is an improvement in winter conditions. During a winter design day the maximum predicted percentage dissatisfied (PPD) has decreased from 42.3% to 21.6% in the zone with the poorest thermal comfort prior to energy renovation (zone marked in orange in Figure 19). The heat demand in the same zone is 37.2% lower during the design day after building renovation. The questionnaire shows that the residents in the building experienced the indoor thermal environment to be poor before the renovation, and experienced problems relating primarily to draughts, low and varying room temperatures, cold floors and the room temperature varying with the outdoor temperature. These aspects have been improved after the renovation, see Figure 21.

Figure 21. Proportion of respondents who experienced problems relating to poor thermal comfort before and after renovation (Paper III).

The residents do not appear to have experienced problems with poor thermal comfort during the summer in the building prior to the renovation. Since the

residents who responded to the questionnaire had not lived in their apartments during the summer after the building had been renovated, nothing can be said about the perceived thermal comfort during the summer. A simulation during a design summer day shows that the maximum PPD has increased from 39.9% to 48.3% in the most solar exposed zone included in the analysis (zone marked in yellow in Figure 19). No solar shading or airing was assumed in the simulation. This indicates that although thermal comfort has been improved during the winter, the problem of poor thermal comfort during the summer may have increased. Measures should be taken to reduce problems, such as external solar shading or airing.

The perception of the indoor environment has improved overall, and the questionnaire respondents perceive the thermal environment, indoor air quality and noise to be better after the renovation, see Figure 22. The most problematic aspect of the indoor environment relates to noise. Although all respondents perceive the noise level to be acceptable or better after the renovation, they also indicate that they have experienced problems with noise from the ventilation system since the building renovation.

Figure 22. Overall experience with the thermal environment, indoor air quality and noise prior to and after renovation of the studied building (Paper III).

6.2 Life cycle cost-optimal energy renovation and primary energy use

Research question 2 - What is the LCC and impact on primary energy use of implementing cost-optimal EEMs to achieve different energy saving targets during building renovation?

Whether or not it is cost-optimal to implement EEMs will depend on many factors, such as the existing thermal performance of the building, the cost of the EEM and the cost of energy. In the studied building, attic insulation has the lowest investment cost but also has limited potential due to the small area and the relatively low U -value prior to renovation. Façade insulation has the highest investment cost per square meter, and the large area means that a significant investment is needed. The energy renovation packages where façade insulation is included as an EEM have the highest increase in LCC per reduction in heat demand. However, insulation of the façade has a large potential to reduce heat losses and is hence required to achieve a high level of energy saving. Installing windows with a U -value lower than $1.1 \text{ W/m}^2\cdot^\circ\text{C}$ is cost-effective in some of the studied energy saving targets.

High energy costs increase the cost-effectiveness of all EEMs, regardless of building type and construction. The cost-effectiveness of implementing EEMs is higher for buildings with poor thermal performance. Paper V includes four different building types, with different thermal performance and construction, heated areas and apartment areas. The two oldest building types (1940s and 1950s) have higher heat losses, and attic insulation is found to be an EEM that should be implemented as part of building renovation to achieve the lowest possible LCC (LLCC). In the two newer buildings included in the analysis (1960s and 1970s), it is not cost-optimal to implement any EEMs to achieve the LLCC. However, the average U -value is reduced since new windows must be installed and will have a lower U -value than the original wood framed windows. Table 13 summarizes the average U -values, heat demand per heated area and LCC per apartment area for the combination of EEMs with the LLCC. The heat demand was predicted using a quasi-steady state heat balance calculation with standardized values for building use. The two oldest buildings with four floors have smaller heated areas (see Table 5) and apartment areas, and thus have higher heat demand and LCCs. This means that it is more expensive to achieve the same energy performance as the two newer five-story buildings.

Table 13. Average U-value with the combination of EEMs found to achieve the lowest possible LCC, heat demand per heated area and LCC per apartment area.

	Original average U-value (W/m ² ·°C)	Original heat demand (kWh/m ²)	LCC optimal average U-value (W/m ² ·°C)	LCC optimal heat demand (kWh/m ²)	Optimal LCC (SEK/m ² apartment area)
1940s	0.94	188.0	0.74	160.5	3699
1950s	0.79	157.0	0.59	129.7	3324
1960s	0.51	113.5	0.43	109.5	3102
1970s	0.50	116.2	0.41	112.1	2911

The EEMs that should be implemented to achieve different energy saving targets vary between the studied building types. Table 14 and Table 15 summarize the U-values and ventilation systems from the combination of EEMs found to be cost-optimal with different energy saving targets in the four studied building types. The amounts of insulation and window types for the different buildings are detailed in Paper V. It should be noted that the combinations of EEMs included in Table 14 and Table 15 are the cost-optimal combinations of EEMs that should be implemented to achieve the defined target. The actual saving could be higher. The cost is far from linear between the different optimal levels. The non-optimal combinations of EEMs required to achieve an energy saving between the optimal levels are presented in Paper V, and show that an energy saving of 10% or 20%, for example, has a higher LCC than an energy saving of 60% in the 1940s building. A predefined and set target for energy saving could thus be problematic and higher energy savings might be more cost-effective than the predefined target.

Table 14. U-values for different building part and heat demand with different energy saving targets for the 1940s and 1950s building.

1940s building						1950s building							
	U-value windows (W/m ² K)	U-value walls (W/m ² K)	U-value attic (W/m ² K)	HRX	Heat demand (kWh/m ² y)	Reduced heat demand (SEK/m ²)		U-value windows (W/m ² K)	U-value walls (W/m ² K)	U-value attic (W/m ² K)	HRX	Heat demand (kWh/m ² y)	Reduced heat demand (SEK/m ²)
Original	2.7	1.03	0.5	No	188.0	-	4 087	2.7	0.77	0.5	No	157.0	-
10%	-	-	-	-	-	-	-	-	-	-	-	-	-
LLCC	1.1	1.03	0.12	No	160.5	14.6%	3 699	1.1	0.77	0.12	No	129.7	17.4%
20%	-	-	-	-	-	-	-	1.1	0.77	0.1	No	125.5	20.0%
30%	-	-	-	-	-	-	-	-	-	-	-	-	-
40%	-	-	-	-	-	-	-	-	-	-	-	-	-
50%	1.1	0.19	0.12	No	76.7	59.2%	4 325	1.1	0.18	0.12	No	72.8	53.7%
60%	1.1	0.17	0.12	No	75.1	60.1%	4 326	0.81	0.12	0.09	No	62.8	60.0%
70%	1.09	0.13	0.09	Yes	56.3	70.0%	6 095	0.81	0.11	0.09	Yes	47.0	70.0%
Max	0.8	0.09	0.08	Yes	48.1	74.4%	6 271	0.8	0.08	0.08	Yes	44.0	72.0%

Table 15. U-values for different building part and heat demand with different energy saving targets for the 1960s and 1970s building.

1960s building						1970s building							
	U-value windows (W/m ² ·K)	U-value walls (W/m ² ·K)	U-value attic (W/m ² ·K)	HRX	Heat demand (kWh/m ² ·y)	Reduced heat demand (SEK/m ²)		U-value windows (W/m ² ·K)	U-value walls (W/m ² ·K)	U-value attic (W/m ² ·K)	HRX	Heat demand (kWh/m ² ·y)	Reduced heat demand (SEK/m ²)
Original	1.9	0.45	0.25	No	113.5	-	3 287	1.9	0.42	0.25	No	116.2	-
LLCC	1.1	0.45	0.25	No	109.5	3.5%	3 102	1.1	0.42	0.25	No	112.1	3.5%
10%	0.85	0.45	0.08	No	102.1	10.0%	3 188	-	-	-	-	-	-
20%	1.1	0.18	0.25	No	90.2	20.5%	3 773	-	-	-	-	-	-
30%	0.94	0.12	0.07	No	79.4	30.0%	3 867	-	-	-	-	-	-
40%	1.1	0.45	0.25	Yes	65.2	42.5%	3 974	1.1	0.42	0.25	Yes	64.8	44.2%
50%	1.1	0.18	0.25	Yes	46.7	58.8%	4 696	1.1	0.18	0.25	Yes	47.8	58.9%
60%	1.1	0.15	0.25	Yes	44.6	60.7%	4 641	1.1	0.15	0.25	Yes	45.8	60.6%
70%	0.8	0.11	0.08	Yes	34.0	70.0%	4 782	0.8	0.11	0.07	Yes	34.8	70.0%
Max	0.8	0.08	0.07	Yes	31.9	71.9%	4 870	0.8	0.07	0.06	Yes	32.5	72.1%
													5 030

In buildings with natural ventilation, ventilation measures are only cost-optimal with very high energy saving targets (70%). The airflow assumed with natural ventilation is the minimum required air flow per heated area and the losses from ventilation are thus relatively small prior to the renovation. The exhaust air ventilated buildings included in the analysis have the minimum required exhaust air flow, and since the buildings have many small apartments the total air exchange rate is high. In the buildings with exhaust air prior to renovation, the ventilation system with heat recovery (HRX) means that ventilation losses are more than halved and this is a cost-effective EEM at an energy saving target above 40%. In fact, no other EEMs need to be implemented to reduce the heat losses by more than 40% in the two studied exhaust air ventilated buildings.

The energy renovation that was performed on the building had a slightly higher LCC than the optimal level, see Figure 23. Instead of insulating the attic, it would have been more cost-effective to add more insulation to the façade to achieve the same theoretical reduction in heat demand as in the performed renovation. The LCC of the building before renovation includes performing inevitable maintenance to keep the building in an acceptable condition, without implementing any EEMs.

Figure 23. LCC and space heating demand for different energy saving targets in the studied buildings, and LCC and energy use from the performed renovation (Paper IV).

The space heating demand was calculated using the quasi-steady state heat balance calculation with twelve time steps. This means that the input data has to be simplified and detailed time schedules for IHG are not possible to use. Standard values for IHG were used. This means that there is a difference in the predicted heat demand for the performed renovation using the quasi-steady state heat balance calculation compared to the heat demand predicted in IDA ICE. The accuracy of the heat balance calculation used in OPERA-MILP was analyzed in Paper IV. A dynamic simulation with the same input data gives a heat demand that is 1.3% lower than the quasi-steady state heat balance calculation of the original building construction and

5.2% higher for the renovated building. The higher difference between the modelled and calculated heat demand in the renovated case compared to the unrenovated case is explained by the internal gains. When the heat losses in a building are small, the IHG constitute a significant part of the heat balance of the building. The monthly time step used in the quasi-steady state heat balance calculation means a risk of mismatch between heat deficit and availability of IHG, such as solar radiation. Thus the useful fraction of the IHG that substitute active heating can be overestimated with a longer time step.

The analysis in Paper IV shows that using a heat pump with an average coefficient of performance (COP) of 3 has a lower LCC compared to using district heating in the studied building. When the operation cost for the heat pump is increased (with a reduced COP or an increased electricity cost), a combination of a heat pump and district heating would be the solution with the most cost-optimal LCC. The heat pump is then used to supply heat during the colder parts of the year, and district heating is primarily used during the spring, summer and autumn when the district heating price is significantly lower in the studied district heating system in Linköping.

The difference in primary energy demand for heating the building varies, of course, depending on the resource intensity of the heat supply systems. The primary energy use in a building using district heating is highly contextualized to the system to which the building is connected. The primary energy factors (PE factors) used in the analysis are found in Table 10. As can be seen in Figure 24, the primary energy use in the three included district heating systems and the average for Swedish district heating systems is significantly lower than the primary energy use based on the PE factors assigned to all district heating systems in the Swedish Building Code.

Figure 24. Primary energy use from the energy renovation of the studied building using district heating as a heat supply system. The x axis represents different energy saving targets, LLCC, before and after renovation.

Figure 25 shows the primary energy using a ground source heat pump as a heat supply system. The primary energy use is significantly lower when the PE factors from the Swedish Building Code are used compared to the factors suggested by the Swedish environmental institute. The primary energy use in the high impact district heating is similar to the primary energy of a ground source heat pump based on PE factors from the Swedish Building Code. However, all district heating systems included in the analysis have a lower primary energy use compared to the primary energy use when the PE factor suggested by the Swedish environmental institute is used for the ground source heat pump.

Figure 25. Primary energy use from the energy renovation of the studied building using a ground source heat pump and electricity as a heat supply system. The x axis represents different energy saving targets, LLCC, before renovation and after renovation.

Using PE factors should reflect the amount of primary resources that an energy carrier uses. By doing so, it is possible to identify less resource-intensive solutions in our energy systems. An important function of PE factors is thus to steer development towards a energy-efficient and resource-efficient future. District heating systems have the possibility to be resource-efficient since they supply a low grade energy carrier and can use both renewable sources and waste as fuels. It is also possible to utilize excess heat from, for example, industrial activities. If the plant is constructed to generate both heat and power, the resource efficiency is even higher. Electricity on the other hand is a high grade energy carrier and is essential for many activities in our everyday life, in industrial processes and in the service sector. Using electricity for heating purposes could be said to involve using an energy carrier with higher than necessary quality. PE factors offer the possibility of comparing electricity with other heat supply systems, such as district heating, under more equal conditions. District heating systems using waste or excess heat, such as the systems in Linköping and Enköping (low-impact system), will have very small primary energy use and it will be difficult for any heating system utilizing electricity to compete in terms of resource intensity, regardless of heat pump COP. Even in a system with higher resource intensity, such as the one in Uppsala (high-impact system), the resource intensity will be lower than a building heated with a heat pump using the PE factors suggested by the Swedish Environmental Institute. The Swedish Building Code assigns all energy carriers except electricity a PE factor of 1. Not only does this mean

that a district heated building is considered to have the same resource intensity as a building heated using oil or natural gas, it also means that the type of district heating system supplying heat to the building is not taken into consideration. Most of the district heating systems in Sweden have PE factors lower than 1, and electricity is generally considered to have a PE factor above 1.6. The current regulation thus favor an energy carrier that is more resource intensive than district heating.

6.3 Life cycle cost of energy renovation versus constructing a new building

Research question 3 - What is the LCC of demolishing an old building and constructing a new building with modern energy performance compared to the LCC of energy renovation of an existing building?

The LCC of renovating the four studied building construction types have been presented and discussed in the previous section. In addition to the LCC presented in Table 14 and Table 15, Paper V includes the cost of renovating the roof so that the building renovation is comparable to the standard of a newly constructed building.

A large proportion of the cost of demolition and constructing a new building relates to the demolition and disposal of the building body. The costs are particularly high for buildings with a body made from concrete because of the weight. Paper V included one building with a concrete frame (1970s building) which has a demolition cost of 3.1 MSEK. The cost of demolition ranges between 1.8 and 1.9 MSEK for the other three building construction types. The cost of operation during the life cycle of the building is small in relation to the cost of demolition and constructing a new building, see Figure 26.

Figure 26. Distribution of LCCs for demolition of the four studied buildings types and construction of a new building (Paper V).

The choice between energy renovation and a newly constructed building includes some aspects that make a comparison complicated. Indoor environment, standard of living or layout might differ, which means unequal conditions for a comparison. Paper V includes an analysis of the costs of renovating a building to the same standard in terms of energy performance as the newly constructed building included in the study. The new building has the same external geometry as the studied building. A standard value for DHW was used in the analysis, and the PE factors from the Swedish Building Code were used to determine the energy performance. The four renovated buildings types differ in terms of heated area and apartment area, but have the same external area. This means a higher cost of renovating to high energy performance in a building with a small heated area and apartment area in relation to the building volume and external area. The four buildings have different electricity demand levels for building purposes depending on the number of floors and ventilation requirements. This means that the buildings all have different maximum heat demand for reaching the energy performance of the new building. All buildings need to have an HRX system to reach the required maximum heat demand. The average U -values for achieving new construction standards by energy renovation can be found in Table 16. The energy renovation measures needed in the two older buildings (1940s and 1950s) are more substantial than those required in the two newer buildings (1960s and 1970s). This is partly related to the poorer thermal performance prior to renovation, but also due to the volume and external area in relation to the heated area. The oldest building is not able to reach the requirements with the EEMs included in the analysis. The two newer building types with the same ceiling heights as the newly constructed buildings can be energy renovated to reach the requirement by insulating the façade and installing an HRX system.

Table 16. Average U-value required to reach same energy performance as newly constructed building and energy performance from needed EEMs.

U_{average} ($\text{W}/\text{m}^2 \cdot \text{K}$)	Annual space heating demand (MWh)	Power demand (kW)	Space heating demand ¹ ($\text{kWh}/\text{m}^2 \cdot \text{y}$)	Facility electricity ¹ ($\text{kWh}/\text{m}^2 \cdot \text{y}$)	DHW ¹ ($\text{kWh}/\text{m}^2 \cdot \text{y}$)	Energy performance ¹ ($\text{kWh}/\text{m}^2 \cdot \text{y}$)
1940	38.7	23.9	48.1	14.8	25	87.9
1950	38.1	24.0	45.6	14.3	25	84.9
1960	49.8	31.3	46.4	13.5	25	84.9
1970	47.3	30.0	45.9	14.0	25	84.9
New	49.6	31.1	46.4	13.5	25	84.9

¹ Primary energy use according to PE-factors in the Swedish building code

Table 17. LCC and renovation or construction cost of renovation to same energy performance as newly constructed building and for construction of new building.

	1940		1950		1960		1970	
	Renovate	Rebuild	Renovate	Rebuild	Renovate	Rebuild	Renovate	Rebuild
LCC (MSEK)	4.57	8.70	4.53	8.60	4.54	8.70	4.53	9.90
LCC (SEK/ m^2)	6 685	9 496	6 485	9 391	4 947	9 498	5 114	10 799
Renovation/construction cost (SEK/ m^2)	5 153	8 147	4 984	8 044	3 596	8 150	3 785	9 451
Energy performance (kWh/m^2)	87.9	84.9	84.9	84.9	84.9	84.9	84.9	84.9

The results from Paper V indicate that, from a cost perspective, it is less expensive to renovate buildings to reach modern energy performance levels. However, renovating the two older buildings requires a significant amount of insulation, making the actual implementation impractical. It should also be noted that older buildings could have important historic value which means that it is not possible to renovate the building in a way that affects its aesthetics or to demolish it.

7 Conclusions

7.1 Research question I

The energy renovation that was performed in the studied building reduced the heat demand by 44%. The indoor temperature during the winter was low before the renovation but was at a normal level afterwards, which means that the indoor climate has been improved. The losses from ventilation have been significantly reduced as a result of the heat recovery ventilation system. Lower heat losses mean that a smaller proportion of internal heat gains are useful for substituting actively supplied space heating. The questionnaires on indoor environment perceptions indicate that the thermal comfort during the winter has been significantly improved as a result of the renovation, and the indoor environment is perceived as being better after the renovation with regard to the thermal environment, air quality and noise. Simulation of the indoor climate also shows that the predicted percentage dissatisfied (PPD) has been reduced in the zone with the poorest thermal comfort during the winter prior to renovation. Simulation of thermal comfort during the summer shows that the PPD has increased and that there is a risk of uncomfortably high indoor temperatures on very warm days without any adaptive measures, such as solar shading or airing.

7.2 Research question II

The study of optimal energy efficiency measures (EEMs) includes four different building types with differences in the thermal performance of the building envelope, ventilation systems, heated areas and apartment areas. For the two newest buildings, it was not cost-effective to implement any EEMs as part of the renovation to achieve the lowest possible life cycle cost (LCC). In the two older buildings with poor thermal quality of the building envelope, attic insulation should be applied to achieve the LLCC. Buildings with small heated areas in relation to internal volume are more expensive to renovate to the same energy performance level compared to buildings with a larger ratio. It is not cost-effective to install a heat recovery ventilation system in the naturally ventilated buildings included in the analysis. In the studied exhaust air ventilated buildings, it is cost-effective to install heat recovery ventilation with an energy saving target above 40% and this is the only EEM needed to reach the target. The primary energy factor (PE factors) for electricity and district heating in the Swedish Building Code favors a ground source heat pump. Using PE factors from the district heating network included in the analysis performed in the thesis favors district heating in terms of primary energy use.

7.3 Research question III

A large proportion of the cost relating to the demolition of an old building and the construction of a new building relates to the demolition and disposal of the building body. The costs are higher for demolishing concrete buildings compared to buildings with lighter construction materials, such as lightweight concrete. The LCC of operating the building is small in relation to the LCC of demolition and new construction. A comparison is made between energy renovations to reach the same energy performance as the newly constructed building included in the study, and the demolition of each building type and the construction of a new building. If the building has very poor thermal performance and high ceilings, it will be expensive to achieve the same energy performance level as a new building through energy renovation. This also requires a significant amount of insulation, making the renovation impractical. In buildings with relatively good thermal performance prior to renovation, it is possible to renovate to the same energy performance level as the newly constructed building included in the analysis with an ambitious energy renovation. The cost of energy renovation to match the energy performance of new building is approximately 30% higher for renovating the studied 1950s building type, compared to the 1960s and 1970s building types. The 1940s building type cannot achieve the same energy performance as a new building with the EEMs included in the analysis. The cost of demolition and constructing a new building is between 40% and 48% higher compared to renovating the 1940s and 1950s buildings to match modern energy performance levels, and almost twice as high or higher for the 1960s and 1970s buildings.

8 Future studies

The main focus of the research presented in this thesis was on the building's energy system. Future studies include expansion of the system boundary to consider effects of energy renovations of multi-family buildings on district heating network. Changes in heat demand in buildings will have an impact on the conditions under which the district heating is produced. In district heating system based on combined heat and power plant, reduction in heat demand of the building sector will have a vital impact on the electricity production as well.

The quasi-steady state heat balance model used in the optimization approach offers the possibility to estimate the potential and cost for energy efficiency improvement for buildings while requiring limited input data and less computational time. However, further methodological development is needed to improve the optimization results especially for buildings with low energy use where internal heat gains represent a significant proportion of energy balance, in order to not overestimate the potential for energy efficiency improvement.

Life cycle costs for energy renovation or new construction are a crucial issue for decision making. Several other practical factors can be important when choosing between these two options. In the case of residential buildings, premises needs and demands are probably similar to when the building was constructed or can be adjusted to fulfill needs. If other building types are considered, such as educational buildings or healthcare facilities, the demand might be very different to when the building was constructed, resulting in limited opportunities to renovate the building to a standard that suits the intended use.

In the analysis included in this thesis, the cost of demolition and constructing a new building have been considered. The rent for a renovated building is often around 70-80% of the rent of newly constructed buildings, and although an energy renovation might have a lower life cycle cost relating to maintaining the building body and heating the building, a newly constructed building will offer higher rental revenue which should be balanced against the higher investment needed for new construction. This has been partially investigated in Paper V that includes an analysis based on rental levels in Linköping, Sweden. The analysis should be extended to include other cities as well as housing companies of various sizes and with different prerequisites. Newly constructed building also provide other benefits that need to be considered, such as daylight levels, noise levels, comfort and well-being, which might not exist in a renovated building depending on the level of ambition of the energy renovation.

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