ENERGY-EFFICIENT RENOVATION AND THERMAL COMFORT ASSESSMENT OF TWO SWEDISH SINGLE-FAMILY RESIDENTIAL BUILDINGS FROM THE MILLION PROGRAM

Shimantika Bhattacharjee

Master Thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centers and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö and Helsingborg. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programs and 2 300 subject courses offered by 63 departments.

Master Program in Energy-efficient and Environmental Building Design

This international program provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behavior and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master program leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

Examiner: Dennis Johansson (Building Physics)
Supervisor: Åke Blomsterberg (Energy and Building Design), Tomas Ekström (Energy and Building Design)

Keywords: energy-efficient renovation, thermal comfort, energy use, indoor thermal environment, the Million Program.

Thesis: EEBD–16/07

Abstract

The energy use in the building sector is increasing rapidly which contributes to the rise in global greenhouse gas concentration. Energy-efficient buildings are considered as healthy buildings due to the improved air quality and comfortable indoor environment. One million residential buildings were built in Sweden during 1965 and 1975 to minimize the acute housing shortage. This initiative was taken by the Swedish government was named as “The Million Program”. Since the residential buildings from the Million Program are old, the indoor temperature is often uncomfortable for the occupants. The occupants of these buildings suffer from health problems due to inefficient ventilation systems and poor indoor air quality. Energy-efficient renovation is important to ensure thermal comfort for the occupants and achieve sustainability in the built environment.

This thesis deals with the thermal comfort issues in two single-family residences built during the Million Program. The research question addressed in this thesis is, *What is the influence of energy-efficient renovation on energy use and thermal comfort in Swedish single-family houses built during the Million program?* The objective is to evaluate different energy-efficient renovation strategies and their impact on thermal comfort for the occupants. A comparative analysis of the thermal comfort condition before and after renovation was explored in this study. Two case study buildings and pre-determined boundary conditions were simulated. Thermal comfort analyses were performed based on the current scientific methods.

This study contributes to the existing knowledge on energy-efficient building design. The results in this study showed that if all the energy-efficient strategies are considered, it is possible to reduce the energy usage up to 70%. Therefore, energy-efficient renovation can bring significant reduction to the energy use. Maintaining a satisfactory comfort level was found challenging. The results revealed that the renovation strategies improved the indoor thermal environment and enhanced the comfort level of the occupants. The findings of this study would be useful to achieve thermal comfort in the single-family residences from the Million Program.

Acknowledgements

The thesis has been supervised by Dr. Åke Blomsterberg, senior researcher and Assistant Professor of the Department of Energy and Building Design, Architecture and Built Environment of Lund University. I would like to express my thankful gratitude to my supervisor for his continuous support in making corrections for each and every draft. His patience, advice and thoughtful ideas helped me immensely to grow up my confidence in writing up my thesis. He helped me continuously with information from different sources for single-family residences. Without him it would have been totally impossible to find those information by myself.

I would like to thank my co-supervisor Tomas Ekström, Energy consultant at NCC. His continuous support in learning the IDA ICE software has been extremely beneficial and helpful for me. He also helped me with different useful links for single-family residences. The guidance through out the study period was extremely helpful to carry out the thesis work. The ideas for hand calculation helped me to solve many difficult parts of the thesis work. The discussion session at NCC were extremely helpful to make corrections for each and every details.

I would also like to show my appreciation and gratitude to my examiner, Dr. Dennis Johansson for his advice and the fruitful discussion of the thesis work. It was very helpful for making the corrections in each of the draft report. His comments were really helpful to fix all of the units and technical stuffs in the report. I would like to mention that the supporting literature regarding the occupancy and schedules given by Dennis were extremely helpful for my thesis.

I would like to thank Dr. Maria wall, the director of the Energy-efficient and Environmental Building Design (EEBD) Master's Programme. I consider myself extremely lucky to be a part of the Energy- efficient and Environmental Building Design Program. I would also like to thank Eliasson foundation who supported this Master's program.

Finally, I would like to thank my family members who have been very patient and supportive throughout the study period. My husband Soumitro was always there with me in every ups and downs during the thesis journey. I am really grateful to him for being so caring and supportive. Special thanks goes to my uncle Mr. Nandan Mukherjee for proof reading the thesis. Whenever I need any help he was always there for me. My biggest inspiration for pursuing Master studies was my parents. Without their moral support it would have been impossible for me to pursue my dream. I must thank God for keeping me fit almost all the time during my Master study.

Shimantika Bhattacharjee

June, 2016

Glossary

ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CAV	Constant air volume
CIBSE	Chartered Institute for Building services and Engineers
DHW	Domestic hot water
g-value	Solar heat gain coefficient
kWh	Kilo-watt hour
MWh	Mega- watt hour
PMV	Predicted mean vote
PPD	Predicted percentage of dissatisfied
$T_{e,ref}$	External reference temperature
T_n	Neutral temperature
TWh	Terra-watt hour
U-value	Thermal transmittance
w	Width of comfort band
WBCSD	World business council for sustainable developement
WWR	Window-to-wall ratio
α	Constant value ≤ 1

Table of Contents

1. Introduction

1.1 Background and problem statement

The energy use in buildings is approximately 40-50% of the total energy use in Europe which results in significant CO_2 emission (UNEP, 2009). The energy policy titled '20-20-20' is enacted to fulfill the target in Europe by the year 2020 (Thollander et al., 2013). The policy aims at improving the energy efficiency by 20%, minimizing the greenhouse emission by 20% and producing 20% energy from renewable sources. Approximately 35% of the European Union's existing buildings are more than 50 years old. The total energy use and CO_2 emission can be reduced by 6% and 5% respectively by improving the energy efficiency of the buildings (Atanasiu et al.,2011).

The building stock in Europe is responsible for CO_2 emission of 678 million ton annually (JRC, 2013). An investigation performed by Ecofys showed that the single-family, multifamily, and non-residential building stock in EU have the potential for CO_2 savings of 60% associated with heating if retrofitting measures are taken into consideration (Tommerup & Svendsen, 2005). Although the new houses are being built efficiently, those are contributing to the potential CO_2 emissions through embodied energy (Power, 2008). The Intergovernmental Panel on Climate Change (IPCC) fourth assessment report shows that the CO_2 emission from buildings' energy use can be reduced by 29% at no incremental cost. The emission reduction is also necessary to offset the adverse impact of climate change on the environment and living components. Limiting the household level energy use without compromising the overall living standards might provide significant emission saving.

Energy use for heating and hot water consumption in residential and non-residential buildings in Sweden is 80 TWh (Statistika Centralbyrån, 2015). This particular consumptive demand is contributing significantly to the increase in greenhouse gas emission. Several reports show that approximately 1% buildings are being added every year to the existing building stock in Sweden. The current building stock is responsible for 27% of the total carbon emission (IPCC, 2007). A newly built home emits 0.86 tons per year. On the contrary, the old house produces an average of 1.6 tons per year.

There is a direct relation between energy use and CO_2 emission. Single-family residences are responsible for over 40% of entire CO_2 emission from buildings (WBCSD, 2007). According to the figure 1.1, 20% comes from dwellings and energy sector which can be sustainably reduced by efficient energy use. It is interesting to note that total greenhouse gas emission was reduced by 20% by the year 2012, although it does not indeed imply a sustainable decrease in the overall greenhouse gas production. It is projected that the building sector might contribute to 17% of emission savings by 2050 if energy efficient strategies are applied thoroughly (International Energy Agency& Energy technology perspective, 2008). Purposive reductions in energy usage without compromising living standards might help in substantial emission reduction.

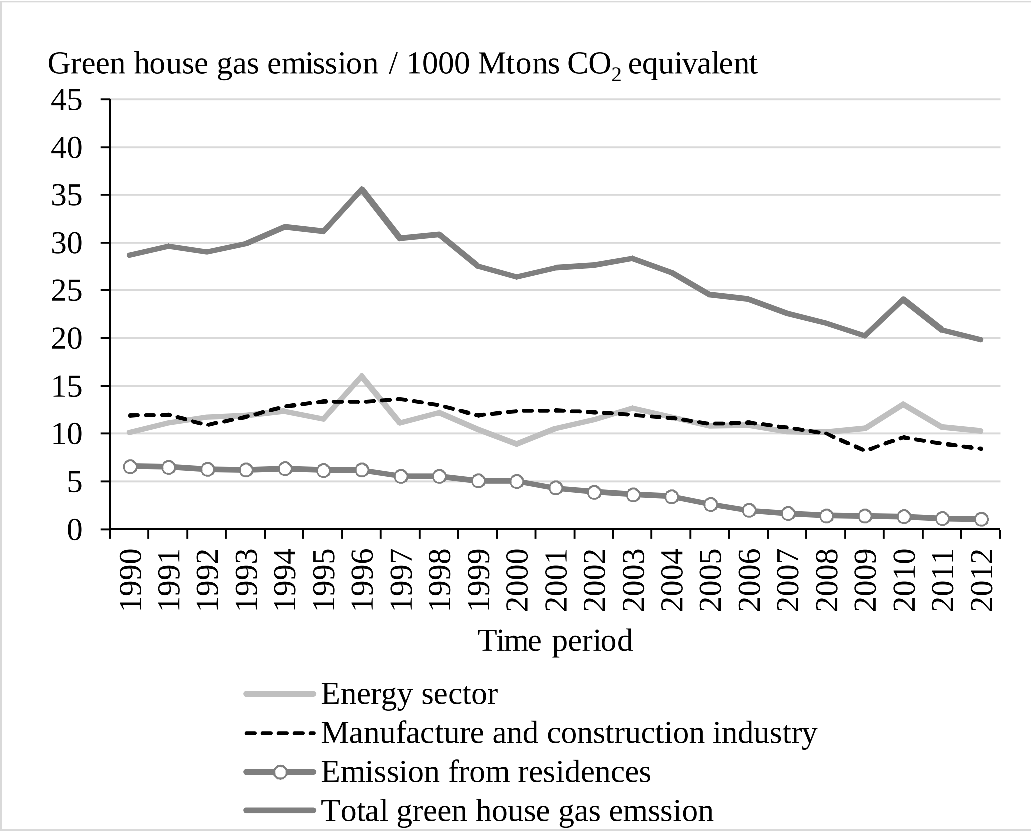

Fig 1.1: Greenhouse gas emission by different sector from 1990 till 2012
Source: Swedish Energy Agency 2013

Since the residential building sector is one of the significant sources of greenhouse gas emissions, possibilities for reducing emission can be achieved through energy efficient measures (Dujardin & Teller, 2014). The tendency for adopting strict energy targets in the building code and energy efficiency standards are becoming popular nowadays (Stephen et al., 2011).

Integration of cost is crucial to find practical solutions for reduction of energy use in building renovation. One important factor for the adoption of energy efficiency measures in single-family houses is dependent on the owner's preference and expectations. A study report by Mahapatra and Gustavsson (2013) emphasized on the economic aspects of the renovation. The following table (1.1) demonstrates the perception of the single-family owners which is derived from the survey results of five consecutive years.

Table 1.1: Percentage of homeowner's preference for the energy efficient measures (heating system and building envelope). Source: Energy renovation of single-family houses: the importance of economic aspects and suggested policy measures. (Mahapatra & Gustavsson, 2013)

Attributes of energy efficiency measure systems	Percentage of homeowners considering the attribute important or most important				
	Survey 2004 (N≈630)	Survey 2005 (N≈392)	Survey 2006 (N≈289)	Survey 2007 (N≈711)	Survey 2008 (N≈1089)
Annual cost of energy	91	95	98	98	90
Investment cost	83	94	93	85	87
Functional reliability	86	84	93	97	78
Indoor air quality	82	80	92	85	68
Environmental benefits	52	55	72	60	62
Increased market value of house	41	48	60	40	53
Greenhouse gas emission reduction	38	43	54	52	40

N = number of the single-family owners participated in the survey

Most of the house owners consider the annual cost of energy as one of the most important factors to adopt energy efficient measures. It can be seen that among other parameters investment cost, indoor air quality and functional reliability are important to be considered. From the table it can be seen that house owners did not consider greenhouse gas emission and environmental benefits as important as other parameters. Therefore, the cost of the energy is an important factor to be taken into consideration while adopting the energy efficient measures. However, the cost implications are often considered as one of the impediments to implementing energy efficient measures. It is expected that energy efficiency measures would maintain the same level of essential service provision to the households by ensuring minimum energy use. A sustainable and rigorous approach is required to obtain energy efficiency in the built environment. Therefore, cost-effective renovation measures may influence the house owner's preference in adopting energy efficient strategies.

Renovation of the existing building is comparatively better than demolition due to less energy use and environmental impact (Sunikka, 2006). Furthermore, the renovation has comparatively higher potential for reducing greenhouse gas emission, whereas demolition of old houses and building new houses increase the risks for CO_2 emission (Power, 2008). Hence, renovating the existing building stock might contribute to reducing the carbon footprint and minimize the burden of waste produced from demolition (Thomson & Filer, 2009).

Since people living in northern climates spend most of the time indoors, it is important to ensure thermal comfort for the occupants. So, the proposed renovation measures need to uphold the welfare related concerns of the residents. However, there exist limited research that shows the relationship between energy efficiency and indoor thermal environment (Singh et al.,2014). The current strategies aims at investigating and crafting different renovation strategies to ensure thermal comfort to the residents.

English Heritage Group in the UK works for the preservation and restoration of older buildings and harness potential environmental benefits from renovation. They found that the perceived thermal comfort level of the occupants was not satisfactory in the restored building (Power, 2008). It underscores that the energy-efficient strategies are connected deeply with the indoor thermal environment which is also influenced by the behavior and activity of the occupants in relation to their thermal preference and expectations (Singh et al.,2010). The result of a long-term study shows that the heating use of a building is mostly affected by the wall conductivity, U value (heat transfer co-efficient), g (solar transmittance) value of the windows and especially if the behavioral parameters are not taken into consideration. Inconsistency in building related parameters can influence the wall conductivity which affects the thermal comfort level of the occupants (Ioannou & Itard, 2015).

The study shows a direct relationship between the energy use of a building and indoor thermal environment. It is important to maintain the indoor thermal environment not only for health issues, but recent studies found that the cost for a poor indoor environment is considerably higher than the energy cost of the building (REHVA federation of European heating, 2012). There is a direct relationship between ventilation system and children health issues (Bornehag, 2014). The study reveals that a house with inefficient ventilation system may trigger an allergy, asthma, and other potential public health problems. Similar examples were found in the UK. An investigation report (North Islington Housing rights project, 1976) by the Chartered Institute of Environmental Health (CIEH, 2006) found that health problems of the occupants living in older buildings could be minimized if the building were insulated properly and the moisture problems were taken care of. Renovated home often overcome such problems. A public health survey named “Värmland study” was performed to evaluate the impact of efficient ventilation system on children’s health. It was observed that houses equipped with efficient ventilation system were at twofold risk than a typical house equipped with the conventional ventilation system.

Besides ventilation system, moisture problems in the walls and condensation on the windows were identified as potential problems deteriorating children health.

The above-mentioned study findings are carefully considered while setting the approach of the current research. It is unequivocal that renovation measures can highly influence the indoor environment. The Economic viability of the proposed measures is also important to implement the energy efficient strategies. However, in this study the cost calculation is not going to be performed.

1.2 Research question and objectives

It is hypothesized in this study that a correctly designed and implemented energy efficient renovation strategy is likely to improve the thermal comfort. Although the international standards for thermal comfort focus on the newly constructed residential and commercial buildings, however, an appropriate guideline for renovating the old buildings are overdue. It is also presumed that energy efficiency is an integral part to obtain the desired satisfaction level of the occupants. Therefore, a number of pertinent assumptions are used to simulate the indoor thermal comfort. The simulations aim at finding the standard parameters to establish an ideal condition for guaranteeing thermal comfort. Another aim is to investigate the correlation between energy efficiency and thermal comfort. The study also explores the extent of the parameters affecting the dissatisfaction level of the occupants. Therefore, this study addresses the following research question:

What is the influence of energy-efficient renovation on energy use and thermal comfort in Swedish single-family houses built during the Million program?

The research question relates to the the following primary objectives of analyzing the effectiveness of the renovation measures in terms of influencing the thermal comfort in Swedish single-family residences built during 1965 and 1975**.**

- What are the factors contributing to energy use and what are the possible renovation measures?
- Which renovation measures have a major impact on the thermal comfort of the occupants?
- What are the changes in the thermal comfort level of the occupants before and after adopting the proposed renovations aimed through efficient energy use?

1.3 Limitations

- The study scope is limited to the houses built over the period of 1960-1977. It does not include any analysis of moisture consequences in the construction phases. However, it should be considered in a real project scenario as it can significantly influence the indoor air quality.
- Examined parameters for energy-efficient strategies are limited to infiltration, insulation, glazing type and ventilation system. The parameterization for the proposed strategies is based on the background study conducted for single-family residences during Million program. The author acknowledges the limitation and proposes the need for further research by considering a wide range of other energy efficiency strategies and robust parameterizations for simulations.
- The study results are derived from simulation results and no physical measurements are used. Thermal comfort assessment method is evaluated through quantitative method. However, the author accepts the need for considering relevant qualitative factors.
- The perception of the household occupant regarding the efficiency of the adopted strategies could add much robustness on the current research. A sample questionnaire survey among single-family households could be conducted. The study is only limited to evaluate the occupants thermal preference based on two proxy indicators: PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) (ISO 7730) .

1.4 Activity flowchart

The following diagram provides a brief overview of the major steps and subsequent activities performed in this study. The diagram consists of three main phases namely as the inception phase, methodological approach and Modelling, thermal comfort study. The pre-processing phase was the initial phase for analyzing the research topic and the corresponding single-family residential buildings. Selection of the two case study buildings was an important step to proceed further into the study. Renovation strategies followed by the simulations were considered as the second phase for conducting the fundamental work. Thermal comfort analysis was performed finally which involved prolem identification and strategic considerations to obtain the optimum result. Figure 2.1 shows a brief overview regarding the actions taken and performed throughout the study.

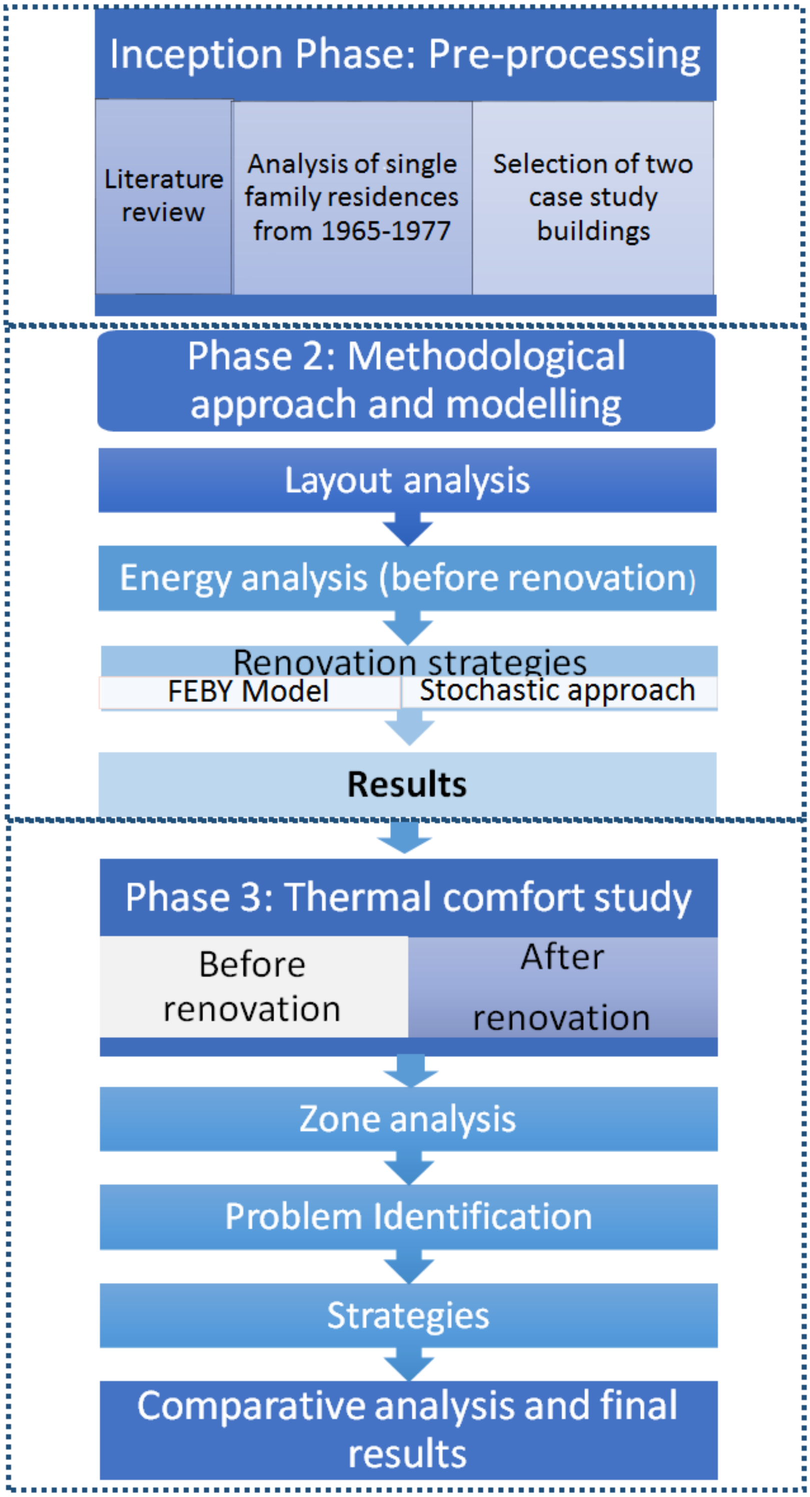

Figure: 2.1: Activity diagram for the actions performed in the thesis

2 Single-family residential buildings in Sweden

2.1 The Million homes Program

One million new homes were built in Sweden under the ‘Million Program’ during 1965-1975 as an initiative to minimize the housing crisis. Sixty percent buildings covered by the program were constructed on new sites (Warfvinge, 2008). The residential buildings built under the Program consists around 25% of the total residential buildings in Sweden. The following graph shows the trend of developing single-family residential buildings in Sweden from 1940 till 2013.

Figure 2.1: Number of single-family residential buildings (1000s) built as a function of year of construction (Statistiska centralbyrån, 2015)

Figure 2.1 presents the year of construction in the X-axis and the total number of single-family residences (1000s) built during the period in Y-axis . It can be revealed from the graph that most of the single-family residential buildings were built before 1940 and during 1971-80. A relatively recent statistics published in 2014 shows that 78% of the single-family houses were built before 1981 (Energymyndighet, 2014). During 2011-2013 around 21,000 new residences were added to the current building stock.

The following figure shows the trend of single and multi-family residential buildings constructed during 1970 to 2014. There is an overall decline in the construction of dwellings since the 70’s. A temporary increase was observed in the early 90’s.

Approximately 266,000 new single-family houses were built during 1961-70, and 414,000 had been constructed during 1971-1980. Similarly, during 1961-1970 the number of newly constructed multifamily residential buildings were 642,000 and in 1971-1980 total of 315,000 houses had been built (Energymyndighet, 2014). Currently, the development trend for developing single-family dwellings is persistingly lower than the multifamily residential buildings.

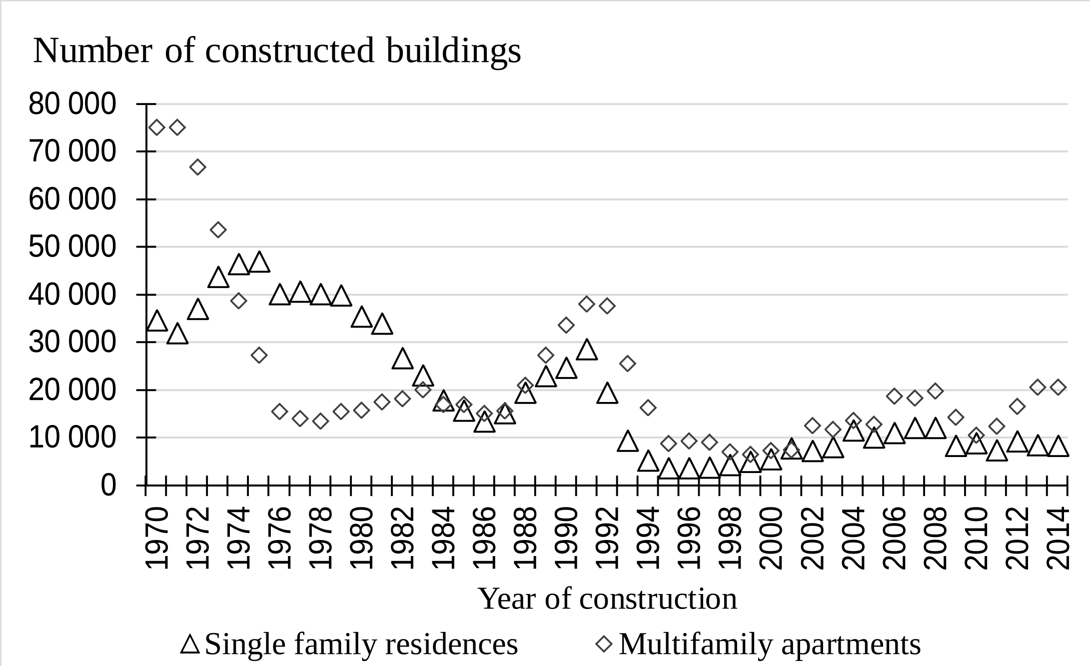

Figure 2.2: Single-family reidences and Multifamily apartments built per year during 1970 till 2014. Source: Statistiska Central Byrån 2014

The current study has chosen the single-family residential buildings from the Million Program era for few reasons which are as follows:

- The residential buildings built during the Million Program were constructed following ‘en masse’ character to achive the resemblance as a group and also to give a notion about the period of the construction. The potential for scaling up the recommendations from the study would be easier to implement because of the structural resemblance. Therefore, unique solutions should be possible to take into consideration for renovating the single-family houses.
- Due to massive production the construction quality and the energy performance was not always satisfactory (Thomas & Viden, 2005). It is a matter of fact that the energy efficiency of the residential buildings was the same in the similar buildings built during the Million Program (Viden & Lundhal , 1992).

Buildings energy use is dependent on geographical position, climate, type of the structure etc. Careful considerations are necessary to identify the potential risks for each particular climate zone. The use phase of a building consumes 84% of the total final energy. The energy is consumed during the operational phase from heating, domestic hot water (DHW), ventilation and electricity use. So, the reduction of energy demand in use phase is important to avoid the increasing energy use in other phases (WBCSD, 2007). Multifamily residential buildings in developed countries use less energy in comparison with single-family residences. It is due to the fact that comparatively smaller wall and roof area reduce energy gains and losses. The corresponding building envelope is smaller which means that less volume is required for heating or cooling (WBCSD, 2007).

The figure represents the energy use for heating and DHW (domestic hot water) and electricity use in single-family residences since 1940 till 2013.

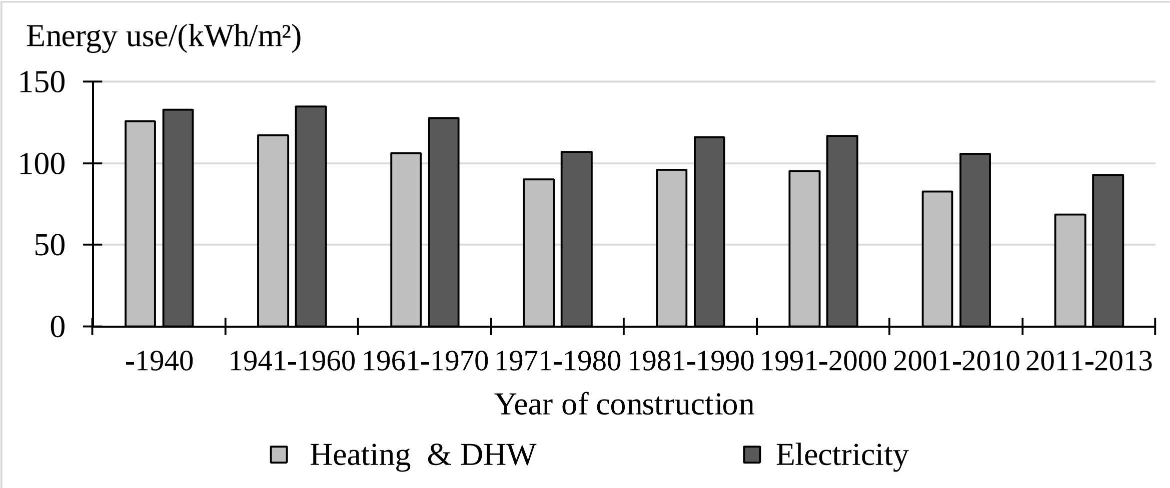

Fig 2.3: Heating & DHW and electricity use in Single-family houses according to the different period. Source: Energystatistisk for småhus 2014

According to the report of Swedish energy agency 2014, the energy use in the residential sector is one-third of the total energy consumption. The single-family house is responsible for around 10% of the total energy use. It is evident from the graph that the single-family residences built during the “Million Program” and earlier has higher energy consumption per square meter area in comparison with new buildings. The single-family homes built after 1968 emphasized on selecting the proper material and construction type rather than energy efficiency standards (Adamson, 2011) Therefore, buildings built during this period were constructed according to the old Swedish building code. The energy use for space and DHW during 1961 till 1970 was 16 MWh/ year or 106 kWh/(m²·year). During 1971-1980 the energy use for space heating and DHW was 13.8 MWh/year or 90.2 kWh/(m²·year) (Energystaistisk for småhus,2014).

In the residential sector, a major part of the energy is used for space heating. The upgraded building envelope helps in reducing the energy use for heating. So, the graph shows a falling trend after the year 2000. During 2011-2013, the energy consumption for heating and domestic hot water was reduced by 35% in comparison with the "Million Program" era. In 2013, electricity use in the residential sector was 71 TWh, which is approximately 51% of the total electricity use in Sweden (Energymyndighet, 2014). Different studies show that residential sector is the second highest power user after industrial sector (International Energy Agency, 2014).

Based on the energy use the graph below shows an overview regarding the changes in the heating system in a different time period. Figure 2.4 presents an overall scenario for the adoption of various types of heating system from 1940 till 2013. The selection of the heating system is based on various parameters namely ventilation system, financial condition, an acceptable level of noise, the size of living area, etc. (Henning, 2010). In Sweden, the use of heat pumps for space heating is the most prominent condition among the member countries within EU. According to the statistical central byrån report 2009, 40% of the single-family residences are heated by heat pumps. Choice of heating system has been changed since the past 30 years. Sweden has the largest number of heat pumps within the member countries of the EU. Almost 40 percent of the single-family houses in Sweden were heated completely or partially by heat pumps in 2008 (Government offices of Sweden, 2008) ; (Energymyndighet, 2014). In early 40's biofuel and electricity was the most popular heating system although the use of heat pump is also noticeable from the graph. Some air-to-air heat pumps afterward contributed to space heating.

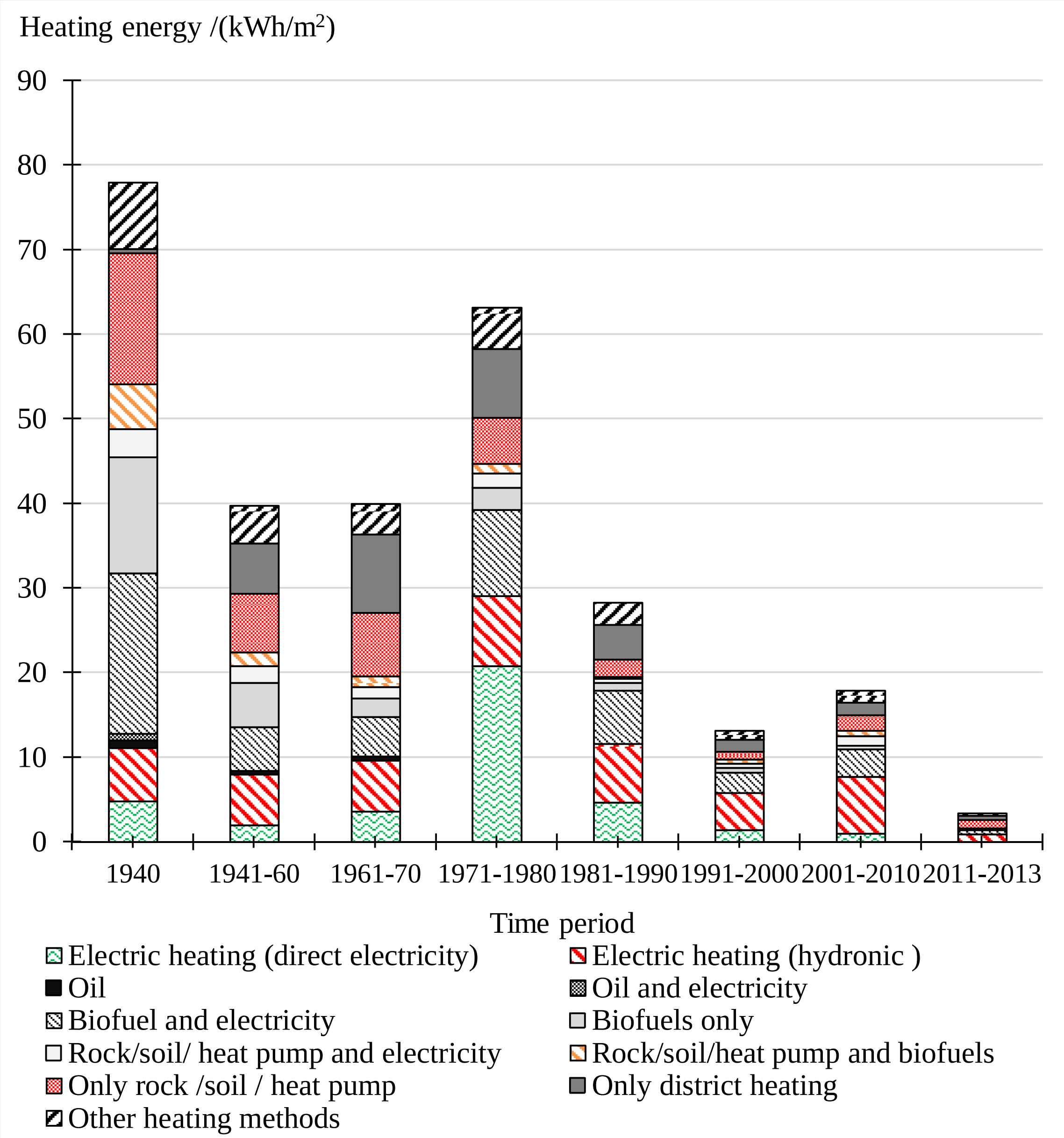

Fig 2.4: Different heating systems adopted in Swedish single-family houses over different period. Source: Swedish energy agency. 2014

The use of air to air heat pumps started to increase slowly in the late 80's and in the year 1990 a total of 9000 pumps were used for space heating. It was followed by a reduction afterwards. Based on the report of the heat pump statistics, the use of air to air heat pump started to increase by 2003 and followed by a peak of 78000 in 2008 (Svenska Kyl och Värmepump föreningen, 2014). It was interesting to observe that during 1960-70 approximately 23% houses were heated by district heating, and more than 20% homes used electric heating as a medium for space heating. Although the scenario changed in 1975, the use of electricity started to rise due to the subsidies or financial incentives that ameliorated the growth of electricity based heating (Perman, 2011).

At present condition heat pumps and electric heating system with hydronic heating are the most common system used by the residents. However, according to the building regulation report 2010 if the house is being heated by the hydronic heating system (electricity) and heat pumps and the installed power demand exceeds 10 w/m^2 then the house will be considered as electrically heated house. So, there is no strict regulation for other heating systems. In addition to that, a national program for energy efficient and energy smart buildings (2005) proposed a new law stating an increase in biofuels as a medium of heating and reduction of the electrical heating system. Consequently, electric heating and household electricity are responsible for around 57% of the heating energy use in single-family houses (Swedish Energy Agency, 2014). All these regulations are aiming at reducing greenhouse gas emissions and efficient use of energy in a sustainable way keeping in mind occupant's well-being.

Heated floor area in residential and non-residential sector is presented in the following graph.

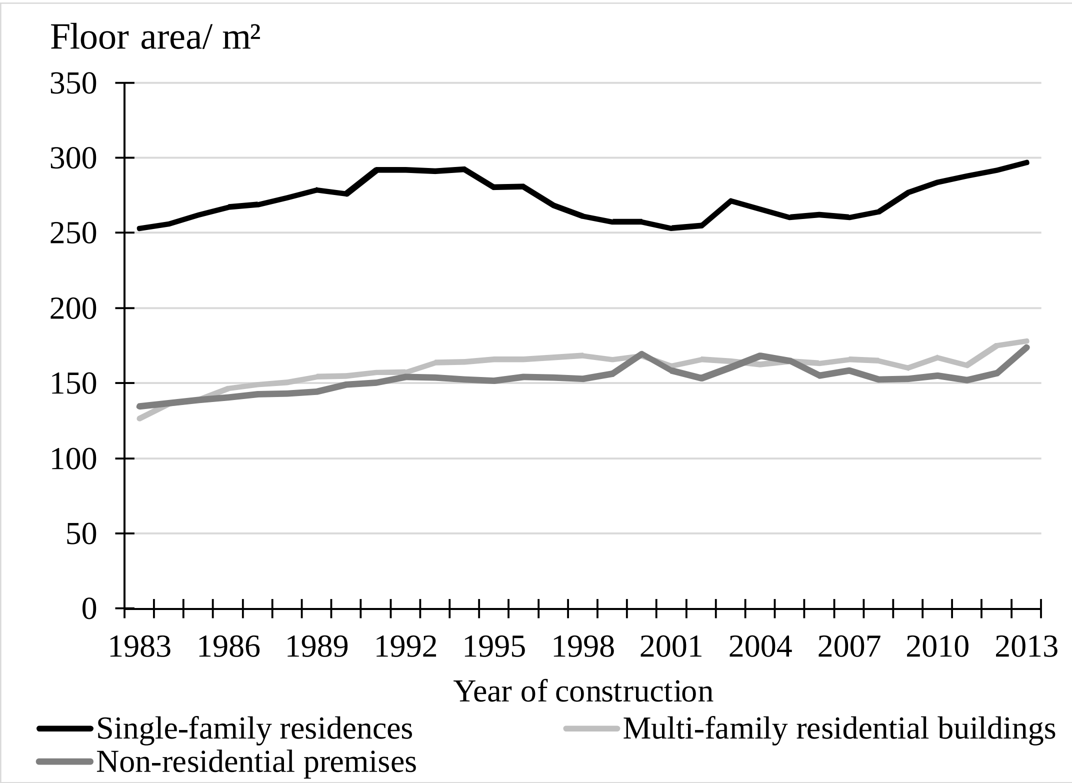

Fig 2.5: Heated floor area in residential and non-residential buildings in different period. Source: Staistiska central byrån,2014

The figure presents a comparative scenario for corresponding heated floor area in the residential and commercial sector including office buildings. Floor area is a direct factor determining particular electricity use (Yohanis et al.,2008). Considering the number of single-family buildings built each year the corresponding floor area is also heading towards an increasing trend. It is evident from the graph that the heated floor area in single-family residences was 297 per m² in the year 2013 which is 40% more than the heated floor area in multifamily residential buildings.

Table 2.1: Different U values and regulations according to different period
(Ghashemi, 2015) and (Carlson, 2003) (Kildsgård & Prejer, 2011) (Adamson, 2011)

Time period	Average U– values / (W/(m²·K))			Code
	Walls	Windows	Ceiling	
1960-1967	0.8	2.78	-	BABS 1960
1968-1974	0.4 - 0.8	2.78	0.25	SBN 67 / BABS 1967
1975	0.25- 0.30	2.00	0.17- 0.20	SBN1975

BBR22 has a specific requirement for average U-value of 0.4W/ (m²·K) for building envelope and specific energy use in four different climate zones in Sweden. The last requirement usually results in lower U-values than required in 1975.

Different studies were performed to evaluate the performance of the residential buildings built during the Million Program. It revealed that in most of the buildings external walls and roof had 10cm of insulation while the standard for minimum insulation was 20cm (Shafqat, 2011). 'BABS 1960' standard was used in most of the buildings constructed during pre-oil crisis period (Hellström & Sandkvist, 2010). The facade consisted of a thin layer of insulation. Due to the absence of continuous thermal barrier in the building enclosure; the building envelope was barely airtight. All these factors contributed to the existence of thermal bridges.

In Building code 1975 not only energy conservation was added to reduce energy use for space heating but also air tightness and balanced ventilation with heat exchangers were added. Implementation of energy conservation was an effort to minimize the oil crisis. It can be seen from the graph that buildings built during the Million Program have comparatively higher U-values for wall, roof and ceiling. Besides insulation, U-values and thermal bridges other factors such as higher infiltration rates and low-efficiency ventilation without heat recovery system were identified as key drivers for the poor energy performance of the building (Warfvinge, 2008).

It was interesting to know the fact that in BBR 22 specific energy use for heating (space heating and DHW) and operational electricity was emphasized instead of U values for building envelope.

The graph below shows the result for U-values conducted by the national board of Housing and Planning (Boverket 2010)

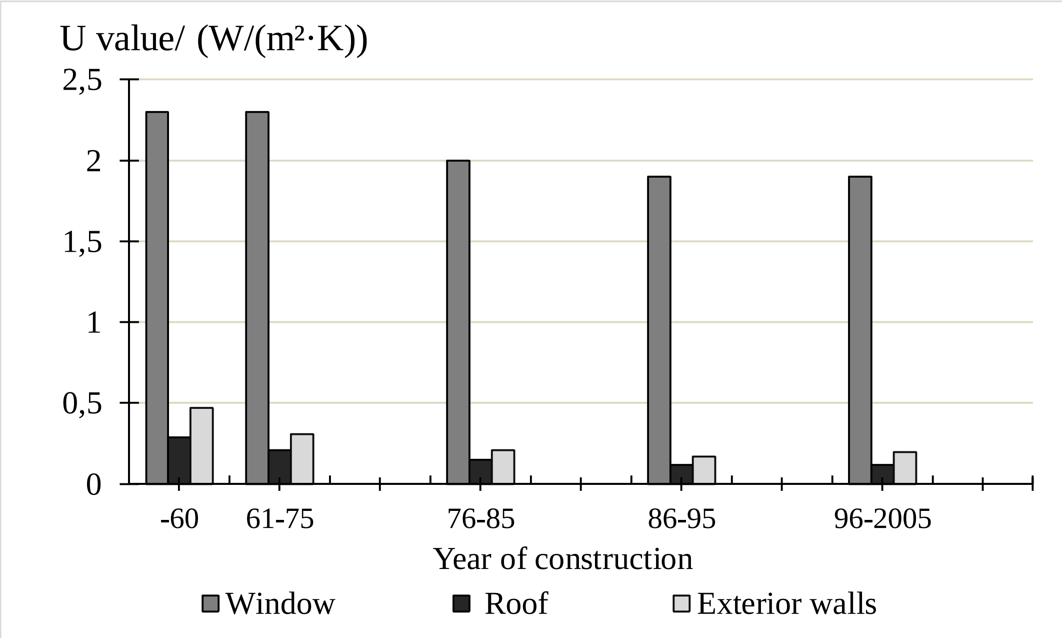

Fig 2.6: Different U values for wall, roof and windows. Source: Based on the result of BETSI survey conducted by national board of Housing and Planning (Boverket). 2010

Reduction of the unintentional air leakage through foundation, wall and ceiling is one of the ways to improve the energy performance of the building envelope. Higher heat loss from the building envelope requires more energy to heat up the building. The insulation and airtightness of the building envelope and construction quality both controls the heat and moisture flows into or out of the building (Elmroth & Abel, 2007). It is therefore, important to improve the airtightness so that the heating system doesn't need to work for too long. After the oil crisis in 1974, the nuclear power growth expanded that helped to give a rise in electricity use for heating. It was subsidized for residential buildings.

The window U value was higher during early 60's compared with new construction with strict building codes. During that period, the aim was to manufacture generic and cheap windows which could easily be ready-mounted in the outer wall (Björk et al.,2011). The graph shows considerably high U-values for external walls in the buildings built before 1960 because more stringent regulations on airtightness and thermal insulation were applied in the building code of 1977. It can be seen (Figure 2.6) that the U value for window and external wall was reduced by 28% and 58% respectively by 2005.

According to the BETSI survey report (2009), natural ventilation is the most common ventilation type in older houses. In newly constructed houses natural ventilation has been replaced by the mechanical ventilation system. Building regulation 22 (1989) introduced a new law stating that demands on heat recovery should be equivalent to a certain percentage of the heated energy from the air. In many buildings requirement met by installing FTX and FVP-system since with these systems it is possible to meet the demand. Around 60% of the single-family residences built during 1986-1995 used heat recovery ventilation air. The requirement for heat recovery was removed in the Board building regulation 23 (1994) for buildings which are mainly heated by renewable energy except electricity.

A government study published in 1943 emphasized on few factors to ensure thermal comfort in traditional residential buildings. Thermal insulation was considered an important parameter for protection against severe weather, energy conservation and comfort for the occupants. Based on the study it can be attributed that ventilation rate should be maintained in such a way that it should not give rise to high humidity level and condensation or moisture problems from indoor surfaces. Thermal insulation should be maintained properly so that it will not generate discomfort during worst climate conditions (Adamson, 2011).

Building code 1975 had a strict requirement on air tightness of the building to avoid unnecessary leakage and condensation. The hygienic condition of indoor environment of the buildings built before World War II was regulated by the national board of health. The required temperature for day and night was 18°C and 16°C respectively for maintaining comfort level of the occupants. Regarding thermal comfort in single-family and multifamily residential buildings a report on “survey of resident’s perceived indoor environment and illness” was published by Boverket. It emphasized that occupant’s thermal comfort in newly built homes is better than older homes (Boverket, 2009). The residents rated living environment as standard in new homes. For all single-family houses, 25% of the residents sometimes perceive drought from windows (not necessarily bad windows, can be from outdoor air inlets close to windows. In addition to that around 4% residents mentioned drought often occurs in the houses built during 1961-1975 (Boverket, 2009).

It was essential to have further overview regarding the thermal comfort conditions in passive house and conventional houses. Figure 2.7 shows the probable reasons for uncomfortable indoor environment in passive house and traditional houses.

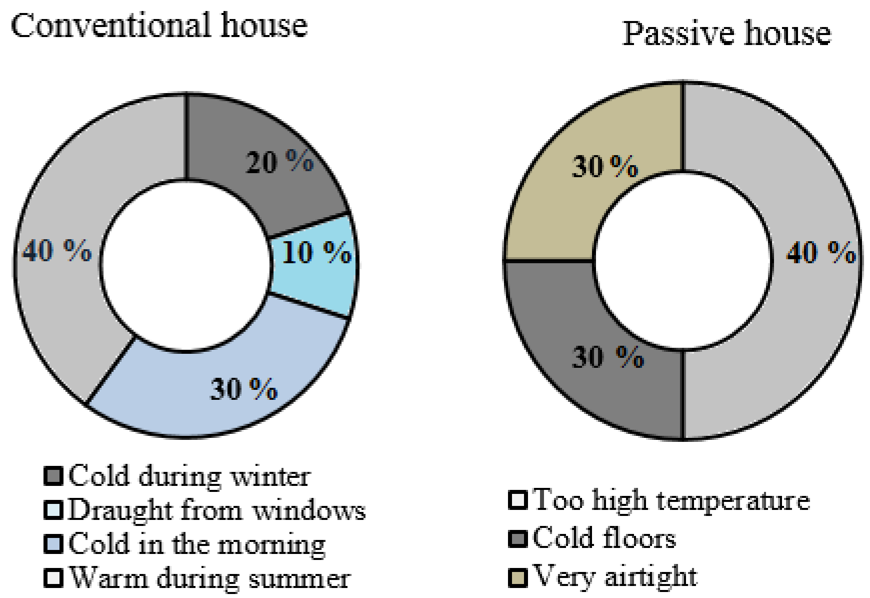

Fig 2.7: Survey result for a post-occupancy questionnaire of the occupants living in a Conventional house and Passive house based on the paper (Rohdin et al., 2014). *Source*: *Experience from nine passive houses in Sweden- Indoor thermal environment and energy use*

Literature study and post occupancy questionnaire helped to identify potential problems in a conventional house and passive house. Earlier research shows that building can be evaluated through a rigorous and systematic way after it is built and occupied (Preiser & Vischer, 2006). Therefore, the assessment of user perception and behavior can be done through post-occupancy evaluation (POE). The reason of discomfort in both of the building types were identified. Figure 2.7 shows that occupants living in a conventional house suffers mostly due to the temperature variations especially a drastic reduction in temperature in the morning and warm during summer period. Although the building envelope is upgraded most of the occupants experience very high temperature during summer. It was interesting to find lower surface temperature on the ground floor of a passive house creating uncomfortable indoor environment for the occupants.

2.2 Building style and architecture

The architecture followed the ancient European style with emphasizes on the roof, balcony or facade detailing during the Miliion Program. The use of lime sandstone on the facade was noticeable. Windows were symmetrical white painted with narrow sashes. Symmetrical white painted windows with narrow sash designed for airing. Gable roof was the most common roof type during 1960 although flat roofs were also noticeable in few single-family houses.

Fig 2.8: Single-family residential building from 1960. Facade made of brick and stucco. Large chimney at the facade Source: Så byggdes Villan: Svensk villaarkitektur från 1890 till 2010.

Special features of 60’s and 70’s architecture style are as follows:

- One and a half plan villa with basement is the most common feature of single-family houses built during 70’s.
- The wooden truss and intermediate floor joists joined in a triangle give the impression of a large pitch roof of 45 degrees and an eave projecting from the facade. The balconies were named as “yodel balcony”.

- The facade height was kept lower and the windows were placed directly under the eaves. The facades are darker with combinations of wood paneling, brick and lime sandstone. The ceilings are made of concrete tiles in new colors or brown and black. Black concrete tiles were still very popular.

- The basement was often designed with a recreation room called ‘gillestuga’. The villas have pitched roofs, masonry facades and gable ends paneled in heavy brown, red, green or blue. In a two story villa, the wider part was designed with a recessed balcony made of wood paneling. The windows were interconnected in the window bands of alternating windows and wood paneling. Single-family houses built during 1970 is a unique example of using new and old facade details. Many houses were built according to the Swedish rural building tradition with Falun Red and mullioned windows after the European building conservation in 1975. A combination of brick and wooden panel dominated.

- On the contrary 1.5 storey terraced houses were painted with green, blue or red colors to create variation with the street. Dormer windows were a special feature for 1.5- storey terraced houses while on the other hand in many group houses single light windows combined with wooden ties and panels were common. Basically the villas were asymmetrically structured which reflects a rational style of architecture.

Fig 2.9: Single-family house, 1970. Facade of yellow painted portrait paneled with brown woodwork situated in a flat land

Figure 2.10: Single-family house, 1970 built in a hilly area. Facade material brick combined with painted wood paneling at the balcony and gable
Source: Så byggdes Villan: Svensk villaarkitektur från 1890 till 2010

3 Description of the case study buildings

The term single-family house means a detached house with one dwelling unit situated in an individual plot. There are no standard size of single-family residences or no specific criteria for average number of inhabitants living in a single-family residences in Sweden. Therefore, two typical layouts representing 60's and 70's were chosen as case study buildings. In Sweden, most of the single-family houses are more than 30 years old and the majority of them need renovation (Mahapatra & Gustavvson. 2013). So, it is reasonable to implement energy efficiency measures. The potential is high to improve the energy efficiency of around 1.9 million single-family houses. Several studies show that energy-efficient renovations can bring about 26% of energy saving potential in single-family residences (Building performance institute in Europe (BPIE), 2015). Due to the individual and private ownership in single-family residences the percentage of renovation in single-family residences is lower in comparison with multifamily residences. Therefore, single-family buildings were chosen for this study to further investigate the influence of energy efficient parameters on the thermal comfort level of the occupants.

Figure 3.1 shows the location of the two case study buildings in the map of Sweden. Case study building 1 is situated in a locality called Åmål and is located in northern part of the Västra Gotaland County. It is approximately 174 kilometers north of Gothenburg, the second largest city in Sweden. It has an area of 481 km² with around 12 thousand inhabitants. Case study building 2 is located in ‘Katrineholm ’which is a municipality in Stockholm County. The municipality is located in the western part of the province named Södermanland. The area is approximately 1189 km² with a population of 32 thousand.

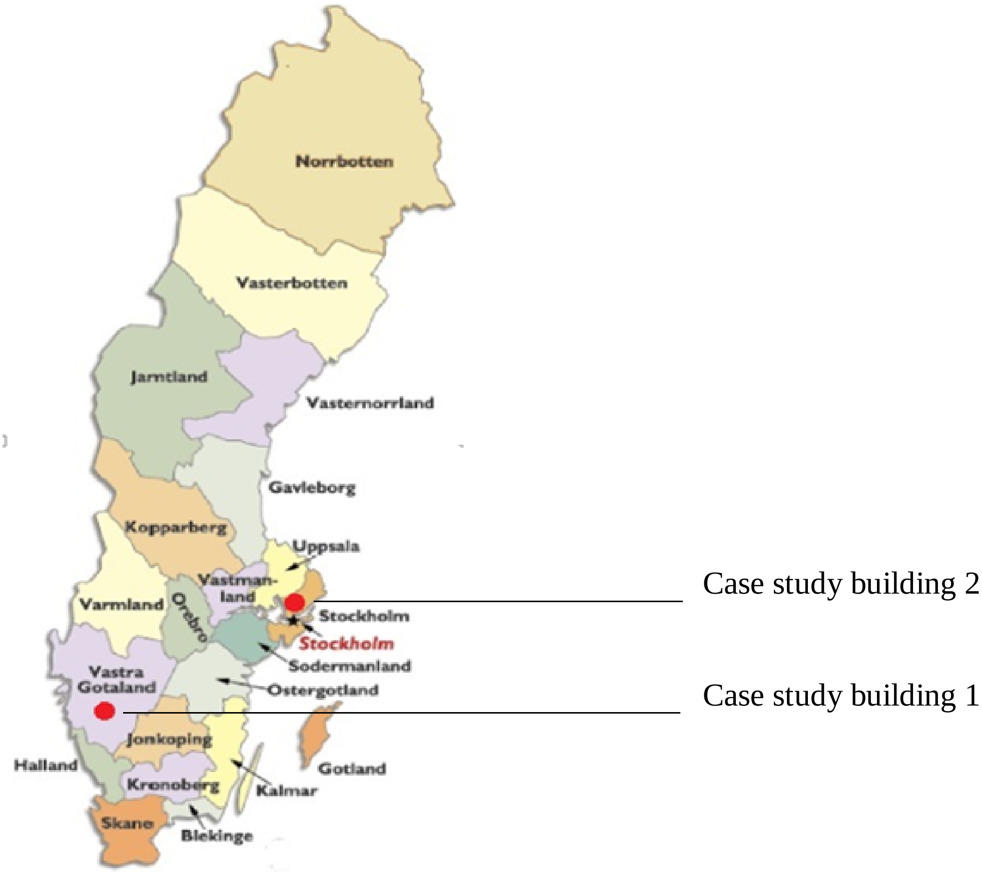

Figure 3.1: Regional map of Sweden

3.1 Case study building 1: Åsa Hus

This sub-chapter introduces the case study building chosen for this study. It is critical to note that there is no tangible information regarding any renovations in Åsa Hus. So, the house is considered as ‘Base case’ since none of the renovations are taken into account throughout this study. Further renovation measures are taken into consideration to evaluate the importance of different energy-efficient parameters.

Table 3.1: General information of case study building 1

Built period	1968
Building Type	Single-family residence -Villa
Orientation	38.2° towards southwest
Floor area	235 m²
Number of storeys	2
Heat and DHW supply	Oil fired boiler
Ventilation system	Natural ventilation (passive stack)

The villa consists of two interconnected rectangles with four respective floors at a different level. Two rectangular building blocks are connected through the stairways, and each of the building blocks has two floors. The height of the building is around 5.3 m. It has a floor area of approximately 235 m^2. The area for service facilities such as laundry, storage, and the garage is included in the 235 m^2 area. However, in the simulation model, the garage was excluded from the A_{temp} (heated floor area) for being an non-heated zone. The service zone, public zone, semi-private and private zones are segregated by the level differences. The basement level consists of laundry, storage and boiler room. The basement level is situated at -2.15 m. At this level, the floor height is 2.1 m. The addition of a garage in the building added a unique feature in the layout. Garage and a recreation room are separated from the basement at -0.75 m level, which has two different entry to separate the public and semi-private zone.

The layout of Åsa Hus is presented in figure 3.2.

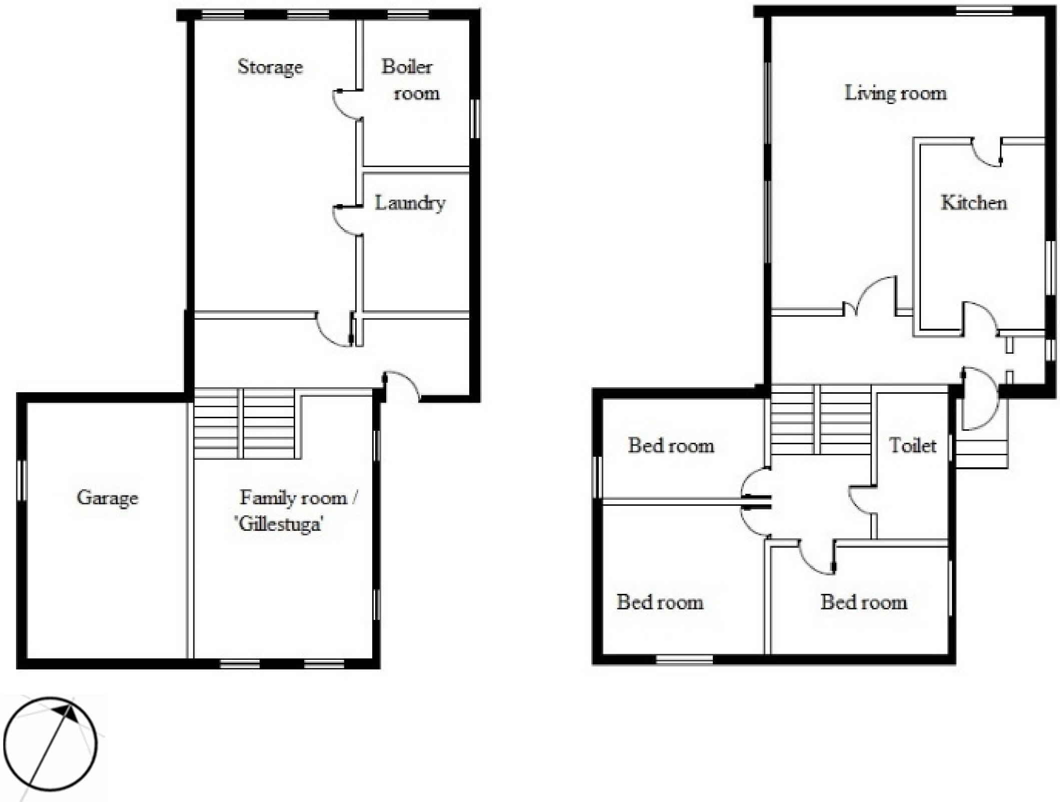

Fig 3.2 Basement plan and ground floor plan of Åsa Hus

The villas built during early 60's often equipped with a large family room and a living rum which was called 'finrum' in general. The family room or 'Gillestuga' is connected with the upper floor through the stairs (Figure 3.2). The ground floor and the first floor levels are situated at 0.15 m and 1.55 m level. Ground level is equipped with a living room, kitchen, and toilet. On the other hand, the bedrooms with a common toilet facility are situated a floor up to create a sense of individual and private space. The kitchen and the connected living room occupied more than half of the plan's surface. The facade is made of lime cement brick with a combination of wood elements, and the roof is made of black concrete tiles. The intermediate floors are concrete slabs. Indoor temperature controlled mechanical regulator with the efficiency of 89% was used for heating (FEBY, 2012).

3.2 Case study Building 2: Villa Katrineholm

Table 3.2: General information of case study building 2

Built period	1975
Building Type	Single-family residence -Villa
Construction Engineer	Sven Aspemyr
Orientation	62° towards southwest
Floor area	150 m²
Number of stories	2
Heat and DHW supply	Electric heating
Ventilation system	Natural ventilation (passive stack)

Villa Katrineholm is rectangular in shape with steeply pitched roof and a balcony above the patio. It has an area of 150 m² with an approximate height of 5.2 m. The facade is made of brick with gabled top and wood paneling. The ground floor has an area of 90 m² with three rooms and a kitchen. Figure 3.3 shows that the upper floor is equipped with a family room, sleeping area and a washroom with sauna facilities.

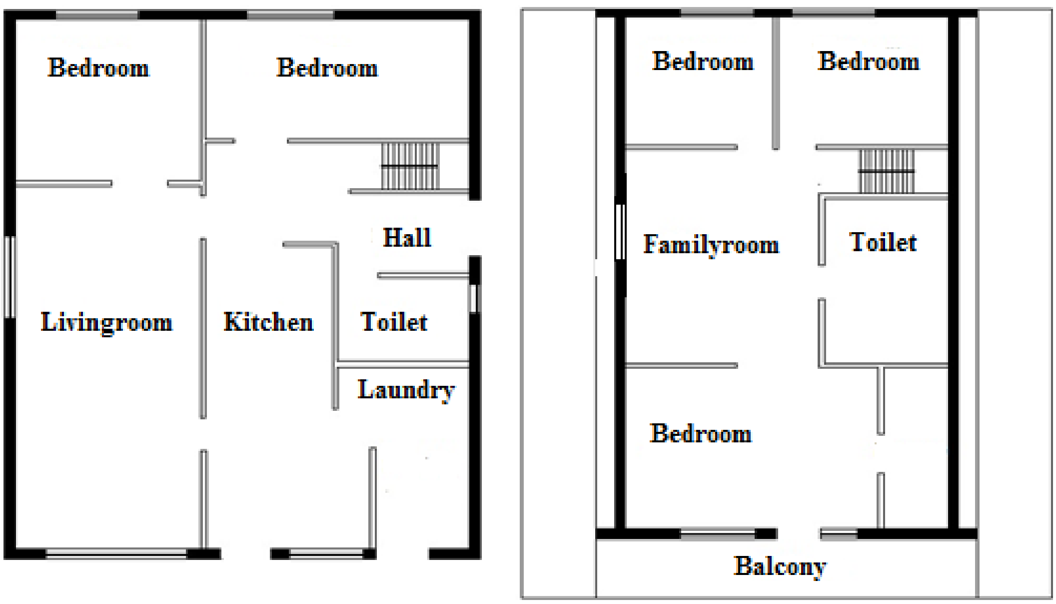

Fig 3.3: Ground floor plan & First floor plan of Villa katrineholm

This type of house was very popular and was in many varieties. Garage and storage are situated in a separate building that is why the area of garage and storage was not included in the heated floor area, A_{temp}. The intermediate and upper floor are formed by the rafters, an extremely economical construction. Unlike the case study building 1 this building is also assumed to be naturally ventilated. As it is mentioned in page number 19 that during the Million Program natural ventilation was the most popular ventilation type in the single-family residences. The heating efficiency of the system is considered indoor temperature controlled electronically programmed regulator with the efficiency of 89 %. It is assumed according to the regulations for existing building provided in FEBY (FEBY, 2012).

4 Methods

The dynamic building energy simulation software IDA ICE has been used to calculate the overall energy consumption in two single-family residences. It enables multizonal analysis of energy and thermal comfort in the building. The software precisely models the building to obtain the energy use and reviews thermal comfort for the occupants based on scientific approaches. Since measured energy consumption are not available, the physical attributes of the models have been constructed according to the data provided in the book 'Svensk Villaarkitekture, Villan' (Björk et al., 2011). The simulations are necessary to evaluate the condition of 'before' and 'after' renovation scenarios in both case study buildings. The method of this study process is divided into three main phases. The earlier section 1-3 provided necessary ground for background study, construction details and layout analysis. The second phase will conduct the analysis through simulations for energy use in the corresponding buildings. The final phase is thermal comfort study which involves both simulations and comparative analysis of the standard equations. It will be helpful to identify the deviations between simulated and standard operative temperature indoor. The materials used during the construction of the building is sometimes difficult to determine, especially when the building is old. It creates discrepancies between the actual and simulated energy use.

4.1 Aim of renovation

The fundamental aim of renovation is to reduce the energy consumption, minimize the environmental impact and improve the indoor air quality and thermal comfort. Conservation of an older building can add value to the social and environmental aspects. Diverse climatic and environmental factors are responsible for the decay in older buildings, which need careful considerations (Meggers et al., 2007). In this study, few renovation strategies have taken into account. The strategies aim at three specific factors namely architectural, environmental and technical.

Table 4.1: Renovation activities based on four specific factors

Factors	Renovation activities
Architectural	• Improvement of the building envelope without changing existing layout
Environmental	• Energy use equivalent to the passive house level • Minimize CO_2 emission
Technical	• Heating and efficient ventilation system • Energy-efficient lighting and equipment use

4.2 Simulation approach

4.2.1 Model setup and boundary conditions

The case study building 1 modeled in this study is a detached single-family residential building with a heated floor area of 208.8 m^2 and volume of 512 m^3. The height of the building is 5.3 m. The attic was excluded from the building to make the model simpler. It is assumed that the roof exchange heat from surrounding air. The garage included in the layout is not considered in the A_{temp} and it is assumed to be a non-heating zone. The climate file and corresponding information is presented in table 4.11. The building is assumed to be naturally ventilated. Leakage paths are included on the surface of windows and chimneys were added over the doors in the model to simulate wind driven ventilation. Air leakage rate of 1.60 $l/(s \cdot m^2) \cdot A_{temp}$ was considered for the simulation of Base case. The internal heat gains from equipment, lighting, solar gains and occupant's body heat have been taken into account for energy simulation of the studied building. The other necessary inputs for running the simulation is presented in the table 4.9 - 4.13.

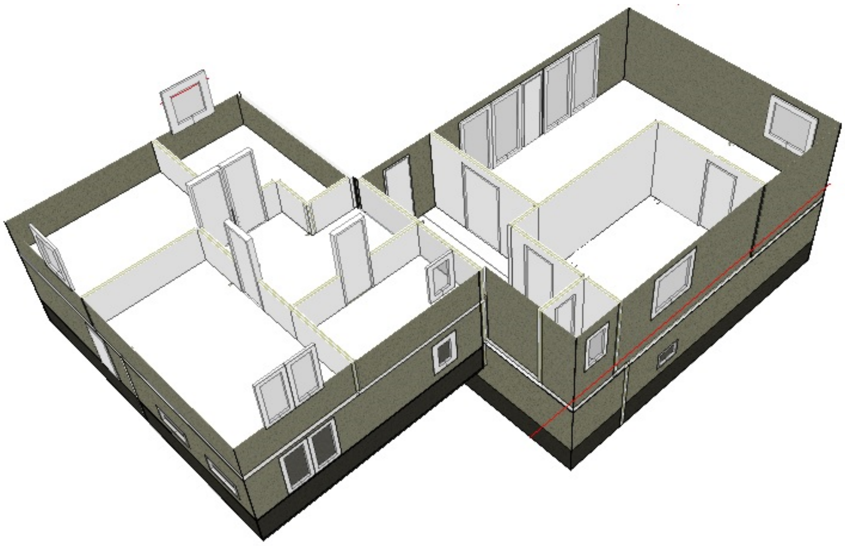

Fig 4.1: Building geometry showing different zones in IDA ICE for case study building 1

Case study building 2 is a two story single-family residential building with a total floor area of 150 m² and volume of 310.4 m^3. The total height of the building is approximately 5.2 m. The building is divided into two levels such as 0 m and 2.6 m. The attic was excluded from the simulation to obtain simplicity in the model structure and to avoid unnecessary errors . A south oriented balcony on the first-floor level has been deducted from the simulation for being an unconditioned space. The zones are assigned according to the layout of the building. The zones have been differentiated by types, i.e., activity, schedule, internal gains, and equipment schedule. The U values were calculated according to the building code of 1975. The construction details for external wall, roof, external and internal floor and the window is presented in Table 4.9 and 4.10. The building is assumed to be naturally ventilated. Leakage paths and chimneys were included on the window and door surface respectively.

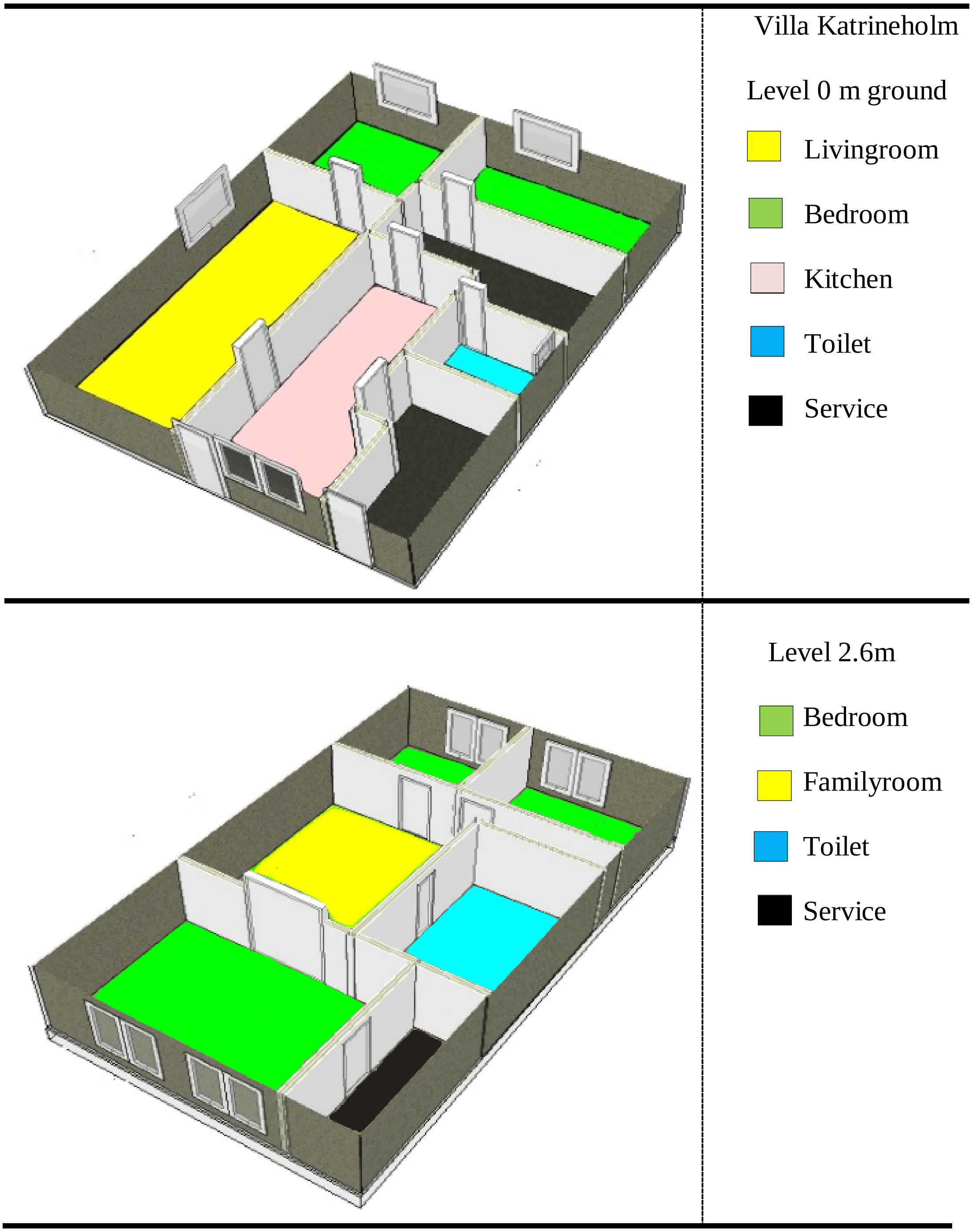

Fig 4.2: Thermal model zones in Ida Ice for case study building 2

4.2.2 Stochastic approach and FEBY schedule for internal gains

The energy calculation of the base case is divided into two specific phase: one with ‘constant’ and another with ‘stochastic’ internal gains. In phase-1, both of the buildings were simulated with FEBY standards for household electricity. The aim was to get an overview regarding the energy use of an average household electricity. An occupancy schedule of 14 hours/day at home (8 a.m-17 p.m away) was considered (FEBY, 2012). An average equipment load of 2.4 W/m² was also used. Analyzing the similar layout of single-family residences and especially the arrangements for bedrooms helped to make an assumption for the number of occupants as 4 and 5 in case study building 1 and 2 respectively. The Swedish standard for monthly distribution of electricity was followed strictly for the simulations (see table 4.2).

Table 4.2: Monthly ratio of household electricity based on FEBY 12[1]

Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
1.25	1.22	1.15	1.00	0.88	0.78	0.73	0.75	0.83	1.00	1.16	1.25

The following figures show the ‘stochastic model’ of household activity patterns by the occupants developed by Widén and Wäckelgår (2010). In phase 2, this scientific model has been followed as a reference model to design the occupancy schedule, equipment load, and lighting. The estimation of the occupancy is based on a probability distribution in each zone. The stochastic approach is a simple way to predicting the occupant’s uncertainty and does not consider the interactions and relationships of occupancy at different times in a zone.The daily activities for equipment, lighting, and occupancy can influence the indoor air quality. That’s why a detailed approach on internal gains and occupancy has been considered to evaluate the impact on energy use. In both of the cases, the household electricity should not exceed the current threshold of 30 kWh/m^2_{Atemp} (FEBY, 2012). The fundamental approach for running both of the simulations was to see how it could influence the total energy use of a building. For the detailed occupancy, lighting and equipment schedule please see Appendix: E.

Figure 4.3 shows the main steps for the activity patterns of the model and figure 4.4 shows the activity profiles for a three person household.

[1] Sveriges Centrum för Nollenergihus
www.nollhus.se/FEBY-12

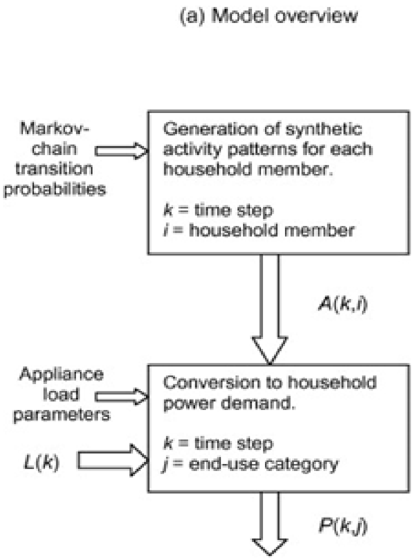

Fig 4.3: Outline of the model. (a) Shows the two main steps involved in the generation of activity patterns A and power demand P together with parameters and input daylight data L(k). Source: A high-resolution stochastic model of domestic activity patterns and electricity demand. Applied energy Volume 87 (Widen & Wäckelgård, 2010).

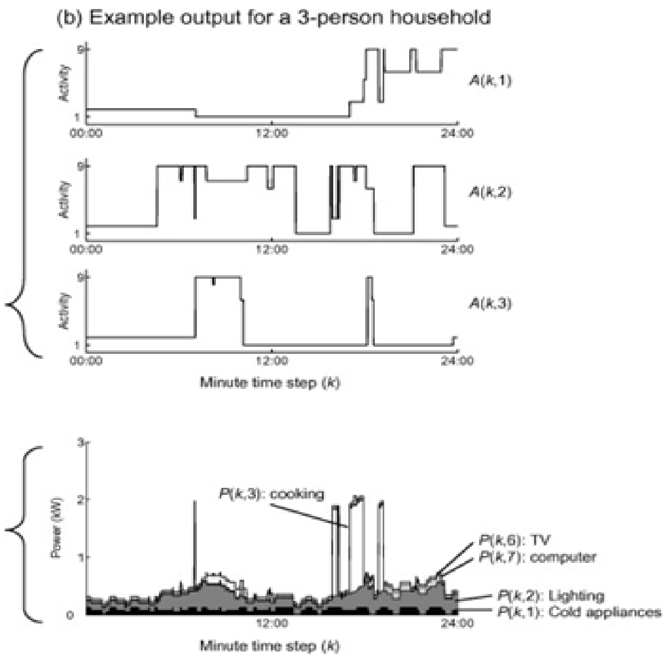

Figure: 4.4: (*b) shows example activity profiles for a 3-person household and resulting power demand divided on different end-use. Source: A high-resolution stochastic model of domestic activity patterns and electricity demand. Applied energy Volume 87* (Widen & Wäckelgård, 2010).

The study considered occupancy behavior, electric lighting and equipment as input in the stochastic model. The patterns in the household are seen as a three state condition called Markov-chain model. The three states are defined as absent, present and active, present and inactive and away. However, the electricity use in a single-family building is based on the set of appliances, the use pattern and the individual demand of each appliances (Widen & Wäckelgård, 2010). The occupancy level has a significant contribution towards the energy efficiency. Previous study shows that it is possible to obtain the net zero energy use in renovated residential buildings through the occupancy level monitoring accompanied by a demand control ventilation system (Johansson et al.,2011). The occupancy level has a profound influence on the household electricity and DHW use. Although previous research shows an in-depth analysis of occupancy patterns in multifamily residential buildings but it helped to determine the importance of occupancy patterns in single-family residences also. The occupancy patterns in stochastic approach have been simulated in this study. The following graph shows the occupancy schedule pattern simulated in IDA ICE for case study building 1.

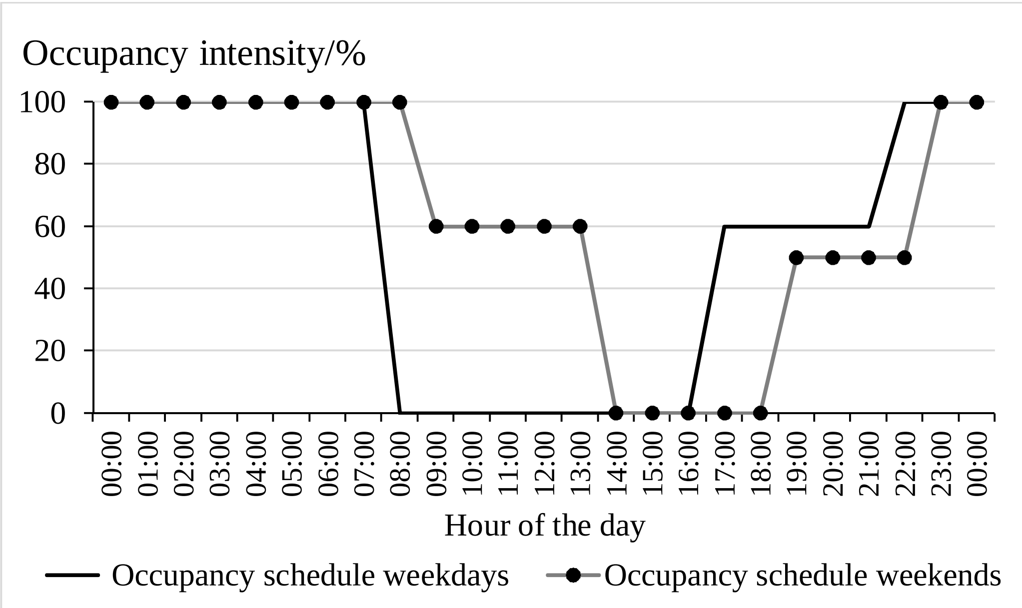

Fig 4.5: Occupancy schedule pattern for weekdays and weekends in Åsa hus

It is observed that the maximum hours are unoccupied during the daytime in the weekdays. The occupants are considered outside from 8:00 am-17:00 pm during weekdays that is why the trend showing a stable scenario during the specific time period. The trend is different during the daytime at the weekend as the occupants are assumed outside between 15:00-18:00 pm. The graph (figure 4.5) shows an increasing trend in occupancy towards the evening hours as the house starts being occupied.

A study by the European database shows that energy use in buildings can be affected by the behavior and characteristics of the occupants (Santin et al.,2009). Therefore, efficient use of lighting can bring potential energy savings. The schedule for lighting is different in summer and winter. Due to longer daytime, the occupants are assumed to be benefited from the daylight. Hence, the dependency on electric lighting is comparatively less in summer period while the scenario is opposite during winter days.

Figure 4.6 shows the simulation result for lighting schedule variation in summer and winter.

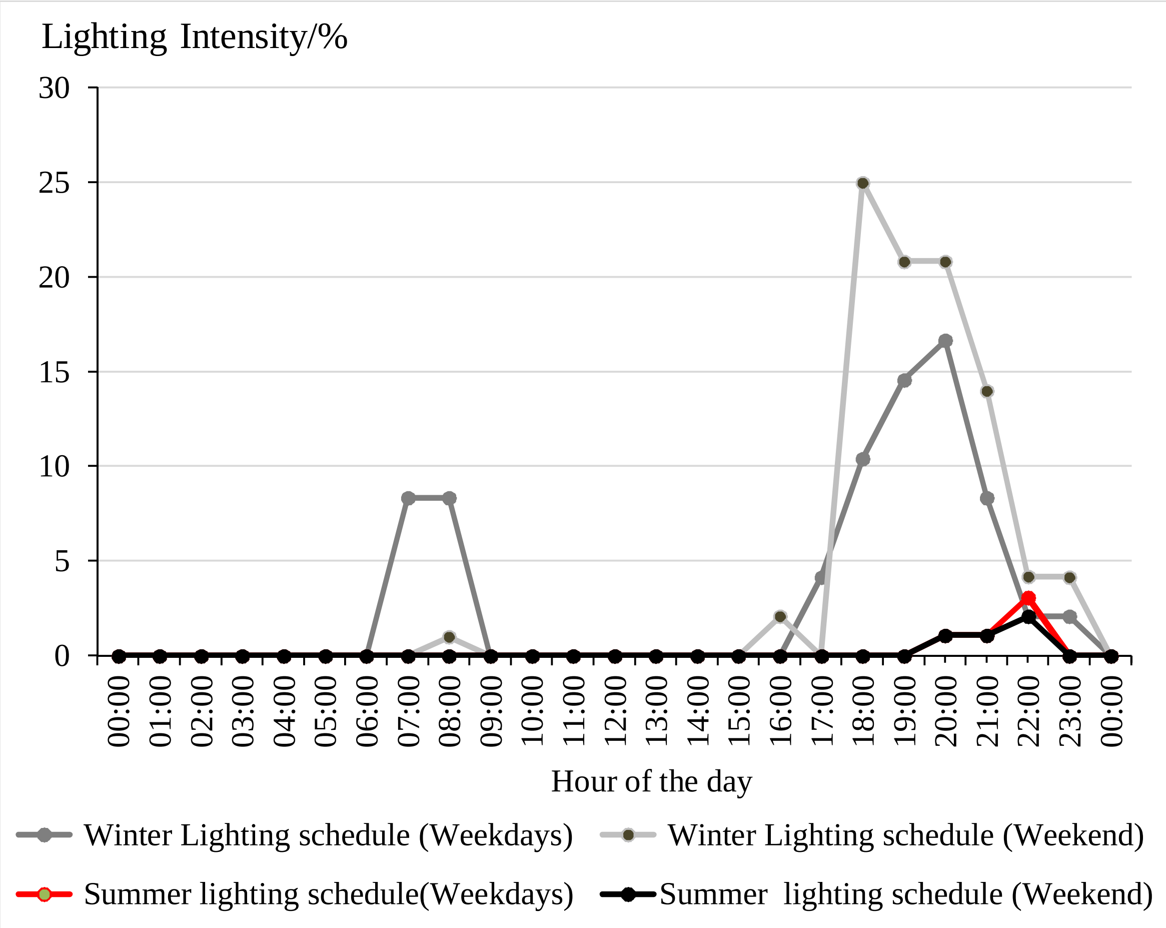

Fig 4.6: Lighting schedule for weekdays and weekend during summer and winter

It can be seen that lighting intensity is maximum during late afternoon and evening in winter (weekend) time. While, summer time experiences the lowest lighting use for both weekdays and weekends. The trend shows stability during 9am till 3pm in the afternoon as the occupants are assumed to be outside. The graph shows 77% reduction in lighting use during summer for longer daytime. During the operational hours, solar gain through the windows can contribute to the total heat gain. The energy intensity for two different scenarios was simulated in IDA ICE, and the result is presented in Table 5.1 and 5.2.

As a detailed calculation on lighting and occupancy were designed, the stochastic model will assess the thermal comfort level of the occupants by combining the influence of outdoor temperature and internal gains. The load intensity in different zones together with the outdoor temperature can be helpful to determine whether it has a positive or negative influence on PPD (predicted percentage of dissatisfied).

4.2.3 Energy-efficient strategies

The following energy-efficient strategies are taken into consideration for both of the case study buildings to make the building more airtight and well insulated to reduce the transmission and ventilation losses. The analysis was carried out for the energy performance of the building to determine the impact of different design parameters. The design parameters were chosen because of their long lifespan. It is important to mention that all of the renovation strategies are considered according to the passive house standard. The passive house standard has been strictly followed in each of the parameters to achieve an optimum solution for the building envelope. The parameters are presented in table 4.3.

Table 4.3: Energy-efficient strategies for improving the base case

	Strategies
1	Improving the external wall
2	Improving the U-value of roof
3	Replacement of windows and doors
4	Infiltration rate
5	Installing a mechanical ventilation system with heat recovery

The renovation strategies aimed at upgrading the building envelope. As a matter of fact improving the existing foundation was not considered in the simulation. The passive standards have been followed strictly according to the FEBY regulations. The required values regarding the U-values and another information is presented in the table 4.9. Further exploration is done to compare the energy use in a newly built passive house and a renovated single-family home after adopting all the renovation strategies. The intention was to improve the external floor construction to see how it can add value to the upgraded building envelope, if it had been possible. Therefore, 400 mm light insulation was placed below the concrete to protect the construction from moisture, and 5mm of floor coating was added afterward on top. Energy-efficient strategies together with the improved floor were simulated to assess the impact on energy use.

4.2.3.1 Improving the insulation of the building envelope

Adding insulation on the facade is a simple way to improve the building envelope by reducing thermal bridges. Considering the age of the building, strategies for upgrading the roof and the external facade is necessary for the sustainability of the building. Additional 220 mm of insulation and 18 mm of rendering was added towards the outside of the facade in case study building 1. The case study building 2 was built towards the end of 70's, therefore, offers a comparatively better building envelope than case study building 1 due to the application of 1975 building code. 200 mm of light insulation was added towards the outside of the external facade in Case study building 2 to improve the performance. The existing insulation and chipboard on inner layers of the roof in both of the case study buildings were replaced by the Extruded Polystyrene and Pavatex insulation board. The U-value was reduced considerably, and FEBY standard was achieved. All the strategies are taken into consideration to make an airtight and upgraded building envelope with a comfortable indoor environment.

4.2.3.2 Replacement of existing windows and doors

The existing building is equipped with double pane windows and poor glazing. The transmission losses through poor glazing can contribute to a significant amount of losses through building envelope. The corresponding heating and is also higher in double pane windows with poor glazing. Replacing energy efficient windows can reduce the energy intensity for heating . The g-value of the window was calculated as shading factors according to FEBY 12. Windows with U-value of 0.8 W/ (m²·K) was used for the sensitivity analysis. The doors of both case study buildings are old and in need of renovation. To reduce the heat losses, an efficient door with U-value of 0.80 W/ (m²·K) was replaced by the existing door to minimize heat losses.

4.2.3.3 Infiltration rate

As already mentioned in methodology section 5.1.2 that both of the existing buildings were assumed to be naturally ventilated. According to the ELIB- report number 7 (Boverket, 2009) the measured airflow in the single-family house is 0.23 l/(s·m² $_{Atemp}$[2]). Therefore, the air leakage rate was calculated by the following steps.

Air leakage rate for case study building 1

$$q_{läck} = 0.23 l/(s \cdot m^2) \cdot 208.8\, m^2 = 48\; l/s$$

Air leakage rate qläck is calculated according to the standard ENISO13789:2008

$$q_{läck} = q_{50} \cdot A_{omsl} \cdot e \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ [1]$$

$$\text{So, } 48 \text{ l/s} = q_{50} \cdot 427.4\, m^2 \cdot 0.07$$

[2] Så mår våra hus- Redovisning av regering suppdrag beträffande byggnaders tekniska utformning . Boverket, 2009

Therefore, at 50 Pa $q_{läck} = 1.60\ l/(s \cdot m^2)$

Air leakage rate for case study building 2

$$q_{läck} = 0.23 l/(s \cdot m^2) \cdot 150{,}3\ m^2 = 35{,}4\ l/s$$

According to equation 1, 35 l/s = $q_{50} \cdot 354\ m^2 \cdot 0.07$

Therefore, at 50 Pa $q_{50} = 1.41 l/(s \cdot m^2)$

The infiltration rate 1.60 l/(s·m²) and 1.41 l/(s·m²) for case study building 1 and 2 were considered as the wind-driven flow for simulation.

Here,

Area of case study building 1 = 208.8 m²

Area of case study building 2 = 150.3m²

The external surface area for case study building 1, A_{omsl} = 427.4m²

The external surface area for case study building 2 = 354 m²

Location of the building depending on the suburban landscape with trees and other buildings, e = 0.07

According to the standard EN13829 described in FEBY 12, air leakage (q_{50}) through a building envelope should have a standard rate of 0.30 l/(s·m²) building envelope area at a differential pressure of 50 Pa. Therefore, this standard value was considered for the sensitivity analysis as a value after renovation. Mechanical ventilation system with heat recovery was chosen as one of the energy-efficient strategies to minimize the ventilation losses. Heat recovery efficiency of 80% was determined. CAV system with supply air and return air flow in different zones were calculated. Air is supplied into living rooms and bedrooms and extracted from toilet, laundry rooms and kitchen. A balanced and Constant air volume system (CAV) is supplied through the exhaust and supply unit combined with a heat exchanger.

The total flow for case study building 1 is

$$0.35 l/s \cdot m^2 \cdot 208.8 m^2 = 73 l/s$$

The total flow for case study building 2 is

$$0.35 l/s \cdot m^2 \cdot 150.3 m^2 = 52.6 l/s$$

Where, airflow = 0.35 l/(s·m²)

The necessary information for the airflow is presented in table 4.4 and 4.5

Table 4.4: Calculated air flow for case study building 1

Supply air flow/(l/s)				Total air flow/(l/s)
Living room	Bedroom (3)*	Family room	others	73
16	33	16	8	

Exhaust air flow/(l/s)						Total air flow/(l/s)
Kitchen	Toilet	Common Toilet	Laundry	Storage	others	73
15	10	16	10	10	12	

*The supply airflow in one bedroom is 11 l/s. The air flow mentioned in the table was calculated for three bedrooms

Table 4.5: Calculated air flow for case study building 2

Supply air flow/(l/s)				Total air flow/(l/s)
Living room	Bedroom(2)*	Bedroom(3)**	Family room	52.6
15	16	12	9.6	

Exhaust air flow/(l/s)					Total air flow/(l/s)
Kitchen	Common Toilet	Toilet	Laundry	others	52.6
10	16	10	10	6.6	

*The supply airflow in the big bedroom is 8 l/s. the air flow mentioned in the table was calculated for two bedrooms.

** The supply air flow in the small bedroom is 4 l/s. the air flow specified in the table was calculated for three bedrooms

4.2.4 Methodological approach for thermal comfort

Thermal comfort is a state of mind expressing satisfaction for the thermal environment (ASHRAE standard, 2013). Research reveals that it is associated with the thermal balance of the body (Fanger, 1970) (Gagge & Nevins, 1976).Thermal comfort is influenced by environmental and individual human parameters. The focus of the study is to explore the key issues that are affecting the thermal comfort in the corresponding buildings. To assess the indoor thermal condition before and after the renovation is the prime target of this study. The impact of the energy efficient strategies in the indoor thermal environment will also be evaluated.

The method of predicting occupant’s thermal discomfort has been investigated through different scientific experiments and activities. The most popular and widespread method is Fanger’s comfort equation and the practical concepts of PMV (Predicted mean vote) and PPD (Predicted Percentage of Dissatisfied). In this study, this method was precisely followed to determine occupants thermal comfort condition indoor. Indoor thermal comfort was evaluated through the simulation results. For specific requirement regarding air change rate, comfort temperature and thermal comfort categories; European standard (EN (15251) and ASHRAE standard were taken into consideration. The simulation was performed for the environmental parameters such as air temperature, relative humidity mean radiant temperature, etc. to see the influence on thermal sensation. According to the standard of ISO-7730, the following factors can affect the thermal comfort level. This are as follows: operative temperature, air movement, clothing level, and activity level.

Different studies show that the periphery of the comfort zone is based on the expected indoor temperature (Givoni & Goldman, 1973). Indoor temperature can significantly affect occupant’s well-being. Indoor comfort temperature with a combination of adaptation is one of the critical environmental parameters in a residential building (Peeters et al.,2008). There are several factors in a residential building that can affect the indoor temperature such as internal gains, outdoor temperature, ventilation rates etc. A detailed schedule was developed on the basis of stochastic model followed by the occupant behavior to assess its impact on energy use and as well as on thermal comfort. Simulations were performed for FEBY and stochastic approach to evaluating the influence of detailed schedule on the comfort level of the occupants. Too warm or cold condition is responsible for thermal dissatisfaction. Certain factors are responsible for affecting the comfort standards of the residents. Surprisingly, the residents in a passive house can feel thermal discomfort. The reasons for thermal dissatisfaction in a traditional and passive house was briefly described in background section (figure 2.7) which has provided necessary knowledge for this particular section.

The following table shows the PPD (predicted percentage of dissatisfied) and PMV (predicted mean vote) according to a different category. The criteria mentioned in the European standard was taken into consideration for the PPD and PMV index for the existing and improved building. The international standard ISO-7730 also takes into account the PPD and PMV index to determine the comfort level of the occupants. It is important to identify which prerequisites meet the specific criteria for considering the environment as acceptable. Thermal sensation scale according to the PMV index ranges between -3 and +3. It is presented below.

Table 4.6: PMV scale according to the standard ISO-7730

3	Hot
2	Warm
1	Slightly warm
0	Neutral
-3	Slightly cool
-2	Cool
-1	Cold

Table 4.7: Thermal comfort categories based on the European standard CEN (Comité Europe én de Normalization) (EN 15251) [3]

Category	Description	PPD	PMV
I	High levels of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like physically challenged, sick, very young children and elderly persons	< 6%	-0.2 < PMV < 0.2
2	Standard level of expectation and should be used for new buildings and renovation	< 10%	-0.5<PMV<0.5
3	Acceptable moderate level of expectation and may be used for existing buildings	< 15%	-0.7<PMV<0.7
4	Values outside the criteria for the above categories. This type should only be acceptable for a limited part of the year	> 15%	PMV< - 0.7or PMV> 0.7

Thermal environment and occupant’s behavior is more dynamic in naturally ventilated buildings than air-conditioned buildings (Baruah et al., 2014). Because

[3] Revision of EN 15251: Indoor environmental criteria: REHVA

www.rehva.eu/.../revision-of-en-15251-indoor-en.

physiological and psychological adjustments are more extensive in naturally ventilated buildings. Existing research shows that an optimum indoor temperature in naturally ventilated buildings is based on outdoor weather conditions. According to the final report of ASHRAE RP-884, the average winter temperature in a naturally ventilated building should be 22.5±1.2 ℃ and the summer temperature should be 23.5 ±1.2 ℃ for 90% thermal acceptability (Dear et al., 1997). Since existing building is assumed to be naturally ventilated, simulations were performed to evaluate the thermal comfort condition of the occupants. The obtained result was compared with the ASHRAE standard to determine the optimum temperature indoor.

The equations developed for neutral or comfort temperatures for different zones of the building is helpful to identify the thermal satisfaction level of the occupants. The method precisely calculates the comfort temperature in each zones and this was one of the reasons for taking this method into consideration. For calculating the comfort temperature in each zones the relevant zone activity and clothing level were chosen. All of the following equations are from Peeters (2008) (Peeters et al., 2008) .The equations are valid for bedrooms and is specified for winter and summer conditions.

$$T_n = 16℃ \; for \; T_{e,ref} < 0℃ \quad \text{……………} \; [2]$$
$$T_n = 26 ℃ \text{ for } T_{e,ref} \geq 21.8 ℃ \quad \text{…………} \; [3]$$

According to CIBSE (Chartered institute of building services and Engineers) the upper limit of comfort temperature in the bedroom is 26 ℃ . Although in ASHRAE standard it was stated that higher temperature is acceptable in a bedroom if a fan is used. However, there is a discrepancy between the calculated comfort temperature and the results from a questionnaire survey from the occupants during summer. Around 50% of the residents described the indoor environment in bedrooms as uncomfortable (Peeters et al.,2008). Therefore, in this study, the comfort temperature 26 ℃ was not considered as a standard for the above-mentioned reasons.

The following equations are calculated for living rooms, kitchen and other rooms.

$$T_n = 20.4 + 0.06 \cdot T_{e,ref} \qquad T_{e,ref} < 12.5℃ \quad \text{...........} \quad [4]$$
$$T_n = 16.63 + 0.36 \cdot T_{e,ref} \qquad T_{e,ref} \geq 12.5 ℃ \; \text{………..} \quad [5]$$

For bathrooms and other rooms $T_{upper} = T_n + \omega\alpha$ …………………[6]

$$T_{lower} = \max(18℃, Tn - \omega(1 - \alpha) \text{…………………} \; [7]$$

Here, $T_{e,ref}$ *= reference external temperature (*℃)

$T_n = neutral\ temperature$ (℃)

$\omega = width\ of\ comfort\ band$ (℃)

α Constant (≤1)

The width of comfort band (ω) and α is different for 10% and 20% PPD.
According to the European standard EN (15251), the renovated building is under the category (II) which states the PPD as less than 10%.
Therefore, $\omega = 5 \; and \; \alpha = 0.7$

The goal is to compare the simulation result with the above-mentioned equations to determine the comfort range for each of the zones. The comfort temperatures were calculated and compared with the simulated result from IDA ICE.

Distinct zones such as living room, bedrooms, and kitchen were simulated to investigate the indoor thermal environment. The living room and bedroom situated towards southwest were simulated with shading to reduce the impact of overheating. The susceptibility level of the occupants can be influenced by the activity level and clothing. The activity level (met) and clothing (clo) were chosen according to the Fanger model. The activity type and clothing was chosen as 0.7(met) and 0.57(clo) respectively for bedrooms. In addition to that, activity type in living rooms and kitchen were 1.0 (met) and 2.0(met). Occupant's position in the room was important as the thermal comfort level can be influenced. It was considered 1.0 m from the facade and 0.8m from the floor level. The following units play a significant role to determine the thermal comfort condition indoor (Nilsson, 2003). In Scandinavia, the following standards are followed.

1 met = 58 W/m^2, Surface area of normal body =1.77 m^2
1clo = 0.155 W/(m^2·K)

It was important to assess the zones with overheating hours. So, shading was investigated for differently oriented zones to minimize the impact. The goal was to optimize the thermal comfort by reducing the high operative temperature during summer. The shading period was set from the 15th of May until the 15th of September. The study was performed only in the bedrooms, living rooms, and family rooms. Different types of shading were simulated in an advanced version of IDA ICE 4.7. The glazing types were chosen accordingly for each shading type. Comparison between the use of exterior Venetian blinds, interior blinds and mid-pane Venetian blind types for each zone was made. Simulations were performed to assess the relative impact of these shading devices on overheating hours.

Thermal comfort criteria in Miljöbyggnad is determined by the PPD index. The following table shows different ranks for achieving a desired thermal comfort level. The criteria are further investigated for two renovated case study buildings.

Table 4.8: Miljöbyggnad criteria for Predicted percentage of dissatisfied (%)

Thermal climate	Bronze	Silver	Gold
PPD (%)	≤ 20%	≤ 15%	≤ 10 %

The simulation result was strictly followed by the Miljöbyggnad category. The minimum value for thermal dissatisfaction was taken into consideration in both ISO-7730 and Miljöbyggnad as 5. The overall steps for performing the thermal comfort analysis is shown in Figure 4.7 .

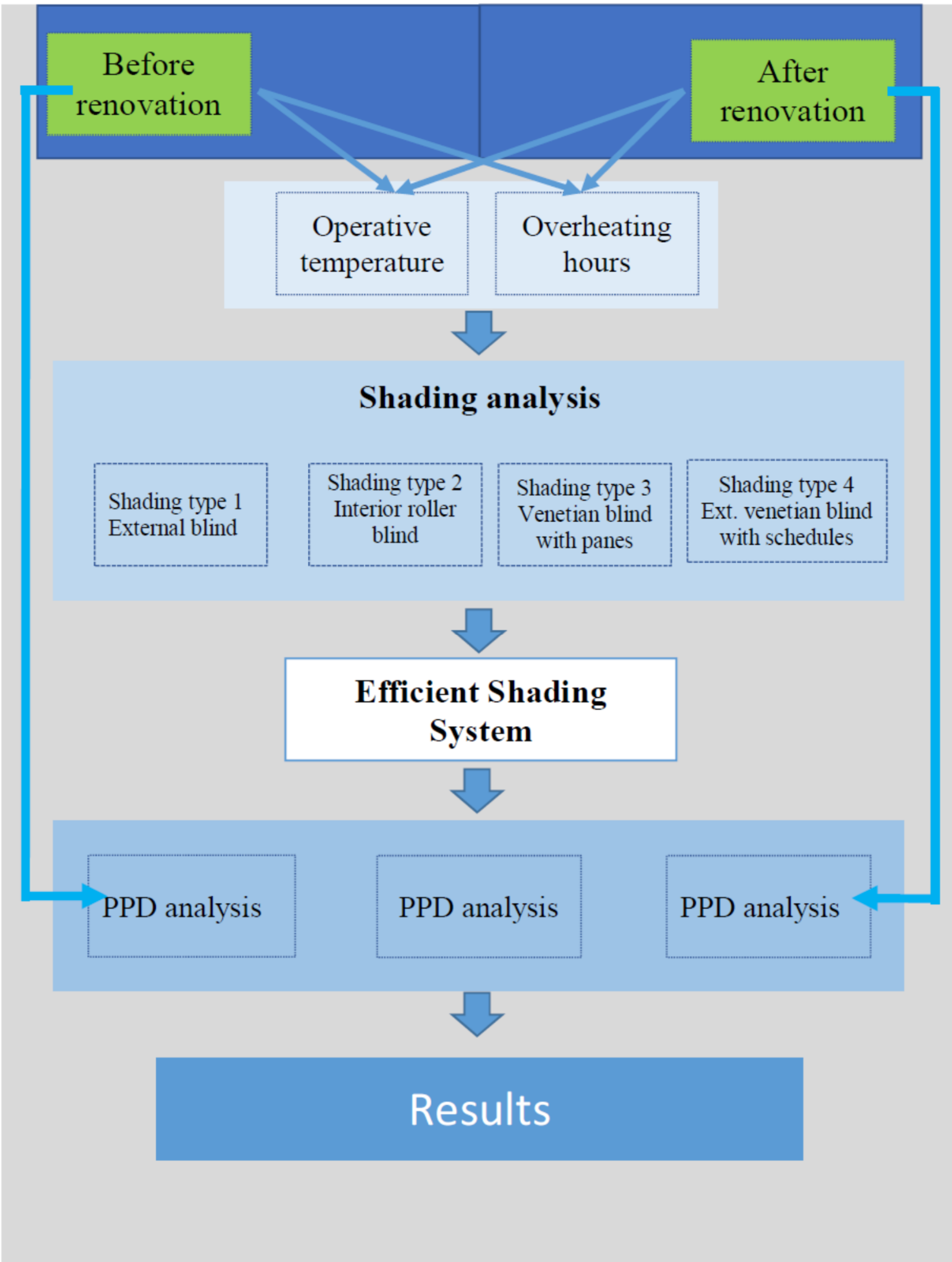

Fig 4.6: Flow chart diagram showing the steps for performing the thermal comfort analysis

4.2.5 Input data

Due to the age factor of the building, it was difficult to get precise information regarding the building construction and other details. The available documents for the building properties and geometry were estimated based on the construction drawings and descriptions from book ‘ Så byggdes Villan : Svensk villaarkitektur från 1890 till 2010 (Björk et al.,2011). In addition to that single-family residences built during 1965-1975 were analyzed to make assumptions of corresponding U-values. The U-value of the foundation is calculated according to ISO-7730. The U value for facade, roof and windows were taken into consideration according to the passive house standard. Input data for building properties are enlisted in Table 4.9. For further queries regarding the input data please check Appendix D.

Table 4.9: Building properties for existing and improved case for case study building 1

Base case	Construction	U- value/ (W/(m²· K))	Improved case	U-value/ (W/(m²· K))
External wall	100 mm Frames cc 600 cross insulation, 17 mm wood and 10 mm gypsum	0.44	Additional 220 mm expanded Polystyrene and 18 mm rendering	0.1
Roof	Wood 17 mm, light insulation 125 mm. and chip board 10 mm	0.26	Additional 200 mm Extruded Polystyrene and Pavatex insulation board 20 mm	0.09
Intermediate floor	Wood 10 mm, chipboard 22 mm, Frames cc 600 insulation 245 mm and Gypsum 26 mm	0.16	the same as mentioned	0.16
External floor	100 mm Concrete, 100 mm EPS insulation and floor coating 5 mm (including ground)*	0.14	the same as mentioned before	0.14
Window	Double pane glazing**	2.9	Triple pane* glazing	0.8
Door	70 mm wood	1.5	80 mm wood	0.81

* For the hand calculation regarding the ground U value please see Appendix: F
* The g-value of the double pane and triple pane windows were considered as 0.5 and 0.37 respectively for case study building 1.

Table 4.10: Building properties for existing and improved case for case study building 2

Base case	Construction	U- value/ (W/(m²· K))	Improved case	U value/ (W/(m²·K))
External wall	60 mm Frames cc600 cross insulation + 120 mm frames cc600 insulation and 13 mm plaster board	0.27	Additional 200 mm light insulation,40 mm gypsum and 10 mm rendering	0.1
Roof	245 mm frames cc600 cross insulation and chip board 80 mm	0.18	Additional 100 mm Extruded Polystyrene (XPS) and pavatex insulation board 80 mm	0.09
Intermediate floor	10 mmWood, 22 mm chipboard, 245 mm Frames cc600 insulation and Gypsum 26 mm	0.16	the same as mentioned	0.16
External floor	150 mm Concrete. 120 mm extruded polystyrene insulation, 22 mm wood and 13 mm plasterboard (including ground)	0.15	the same as mentioned	0.15
Window	Double pane glazing	2.6	Triple pane glazing	0.8
Door	70 mm wood	1.5	80 mm wood	0.81

* The g-value of the double pane and triple pane windows were considered as 0.5 and 0.37 respectively for case study building 2

Table 4.11: Input data for values and sources

Data	Source and corresponding values
Weather file	According to the climate file of Gothenburg and Stockholm from database of IDA ICE software
U values	Estimated based on the drawing from book “Villan: Svensk Villaarkitektur från 1890 till 2010” and documents regarding småhus built during the Million program
Interior lighting intensity/(W/m^2)*	1.16
Internal gains from people/(W/m^2)*	1.54
Internal gains from equipment /(W/m^2)*	2.32

*Interior lighting, internal gains from equipment and occupant, is calculated according to the SVEBY requirements for småhus. Source: Energy data analysis for småhus FEBY.

Table 4.12: Input data for Base case[4]

Data	Values
Infiltration rate/($L/(s\cdot m^2)$) at ± 50 Pa pressure difference for case study building 1	1.60
Infiltration rate/($L/(s\cdot m^2)$) at ± 50 Pa pressure difference for case study building 2	1.41
Thermal bridges incl. in U values/%**	25
Domestic hot water/ (kWh/m^2)	20
Heating set point /℃	21
Cooling set point /℃	25
HVAC template	Natural ventilation

[4] Sveriges Centrum för Nollenergyhus
http://www.nollhus.se/dokument/Kravspecifikation%20FEBY12%20-%20bostader%20sept.pdf

*Due to the age of the building. It was assumed that the infiltration rate would be high (Fennel & Haehnel, 2005).
**For existing and new construction the thermal bridge is considered as 25% and 20% respectively. The thermal bridge calculation is added in the appendix B.

The technological advancement paves the way for increasing electricity use in the household. Inspite of the improvement in the energy efficiency the increase in the carbon footprint is also prominent in the modern appliences. Table 4.13 shows the list of appliances used in different zones. However, it is important to note that the following data is used for stochastic approach only which is briefly described in the methodological approach.

Table 4.13: Use of different appliances in household activities at different zone[5]

	Appliance	Power	Operation time	Time/(hour/ year)
Living room	Tv	67	2h/day	728
	Internet router	5	continuously on	8760
	Hometheatre projector	200	0.5 hours a week	26
	Vacuum cleaner	500	1 hour a week	52
Bedroom	Desktop computer	200	9.5 hours a week	495.35
	laptop	65	14 hours a week	730
	Tablet computer	10	11 hours a week	573.5
Laundry	Washing machine	500	6 hours a week	313
	Tork drier	1000	2hours a week	104.28
Kitchen	Electric oven	1000	1.5 hours/ day	390
	Microwave oven	800	1/2 hour per day	182.5
	Refrigerator	180	continuously on	8760

[5]Power of typical household appliances
https://www.daftlogic.com/information-appliance

5 Results

5.1 Comparative analysis of FEBY schedule and stochastic model

The section presented below shows the outcome from the sensitivity analysis performed for two case study buildings. It was conducted for two different scenarios namely as FEBY schedule and stochastic model.

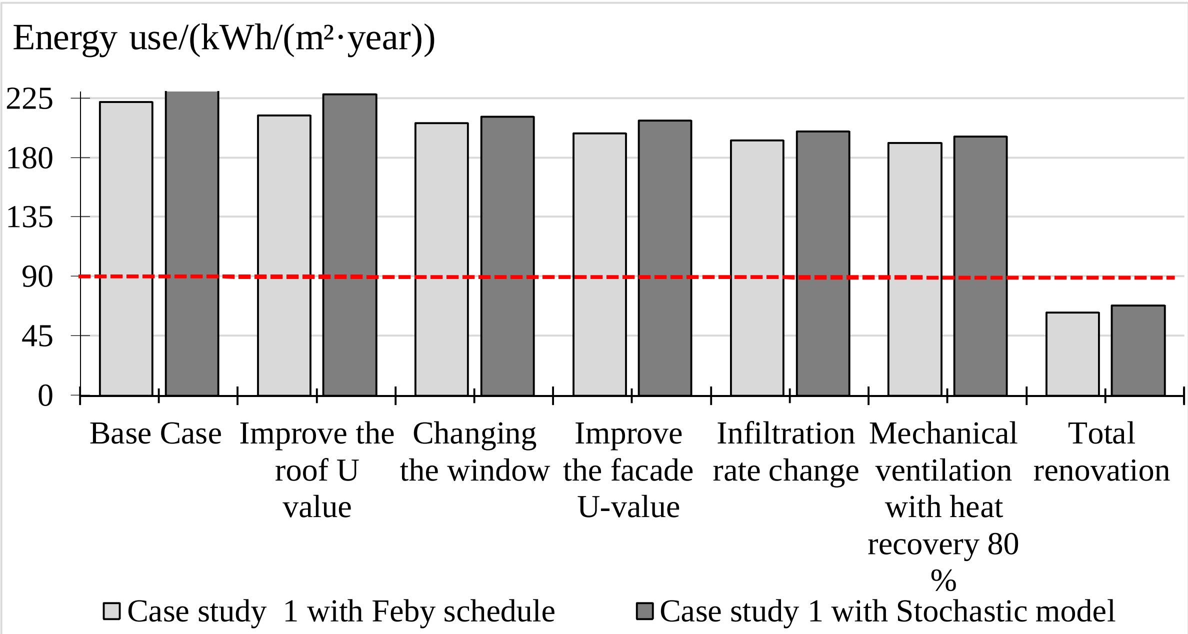

Fig 5.1: Simulated energy use for heating and DHW (domestic hot water) in base case and other renovation measures in case study building 1

All the renovation measures were taken into consideration based on the passive house standard demonstrated in FEBY (FEBY, 2012). The dotted line represents the BBR threshold limit for energy use in single-family residences which is 90 kWh/m² in climate zone 3. As it is evident that the difference in energy use is insignificant for all of the parameters, therefore, the individual renovation measures could not achieve significant reduction in energy intensity. The energy use in the base case is very high because the building envelope is not airtight enough and is poorly insulated. Among all the other parameters, mechanical ventilation with heat recovery has the maximum energy savings of 31 kWh/m². Although mechanical ventilation was introduced, it could not reduce the energy intensity to a higher degree. The ventilation rate was higher which results in only 13% and 15% reduction in energy use. The total renovation measures resulted in annual energy use of 62.8 kWh/m² and 68.1 kWh/m² in case 1 and 2 respectively, which corresponds to 73% and 70% energy reduction in comparison with the base case. It was evident that the total renovation measure is highly beneficial in terms of reducing the energy intensity but implementing individual measures could not contribute to potential energy reduction in both FEBY and stochastic model. The stochastic model is simulated with each zone specific schedules and corresponding schedules for summer and winter time. On the contrary, the FEBY schedule is simulated with a general overview for internal gains and no specific schedules are considered for each of the appliances used in the residence. Hence, it is evident from the graph that energy use in the stochastic model is comparatively higher than the FEBY model. Apparently it seems that FEBY model is more energy saving than the stochastic model. It is due to the fact that stochastic model has a detailed schedule regarding lighting, internal gains, and occupancy. Moreover by implementing all the renovation measures, the calculated energy use in two cases are approximately 30% and 24% lower than the BBR standard.

Concurrently, the scenario is the same in case study building 2. A similar stochastic schedule has been considered for the simulation in comparison with the standard FEBY schedule. The energy intensity for heating and DHW (domestic hot water) in the base case is 209 kWh/m² and 217 kWh/m² for FEBY and stochastic model respectively.

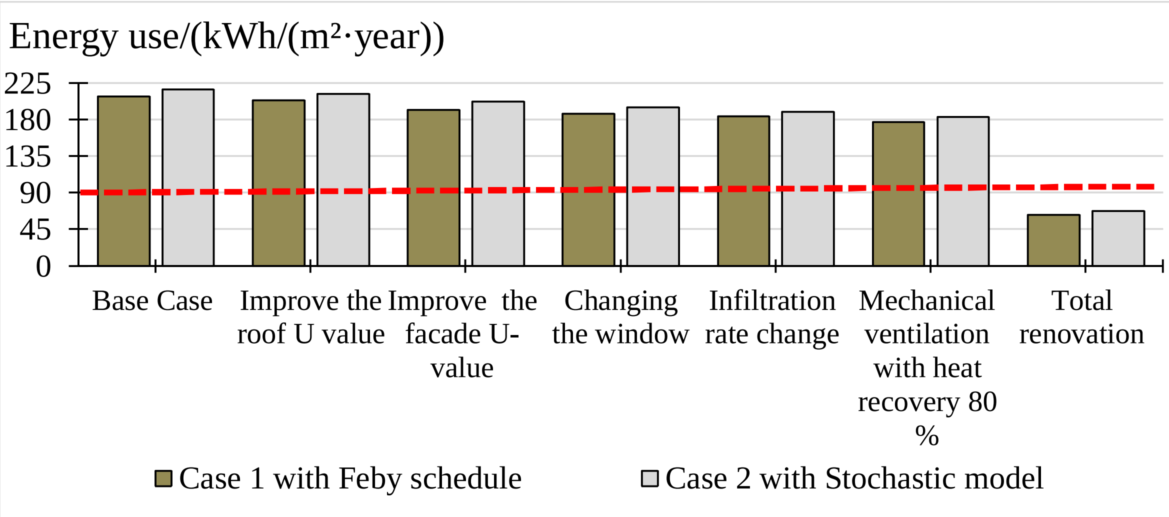

Fig 5.2: Simulated energy use for heating and DHW (domestic hot water) in base case and other renovation measures in case study building 2

Upgrading the roof has the minimum contribution towards the reduction of energy use. However, individual energy efficient strategies showed a reasonable reduction for heating in both FEBY and stochastic approach (see Figure: 5.2). The simulated result for stochastic model is showing an increase on energy use by 4.2 kWh/m² in the case of total renovation. Among all other parameters, the mechanical ventilation with heat recovery efficiency of 80% reduced the heating energy by 31% . In addition to that the heating use in the case study building achieved was 177 kWh/m². Energy intensity in total renovation for both of the model is 63.2 kWh/m² and 67.4 kWh/m². The following results show the final energy use for the total renovation based on FEBY schedule and Stochastic Model.

Table 5.1: Energy use in case study building 1and 2 based on FEBY model

	Åmål		Katrineholm	
Energy use	Energy/ kWh	Energy /A_{temp} / (kWh/m²)	Energy /kWh	Energy /A_{temp} / (kWh/m²)
Heating	7901	37.8	5742	38.2
DHW	4200	20	3019	20
Auxiliary energy	1051	5	756	5
Final energy use	13152	62.8	9517	63.2

Table 5.2: Energy use in case study building 1and 2 based on stochastic model

	Åmål		Katrineholm	
Energy use	Energy/ kWh	Energy /A_{temp} / (kWh/m²)	Energy/ kWh	Energy /A_{temp} / (kWh/m²)
Heating	9000	43.1	6379	42.4
DHW	4200	20	3019	20
Auxiliary energy	1051	5	756	5
Final energy use	14251	68.1	10154	67.4

*The auxiliary energy takes into consideration the energy for fans.

5.2 Heating use in base case and renovated building

Simulations for improving the external floor is performed, although it is a very complicated and expensive renovation measure. Figure 5.3 shows the monthly heating use in the existing building and renovated case study buildings. The heating use shows a descending trend towards the warmer months which starts to stabilize during the summer months and starts to increase substantially as the colder months approaches. An airtight building envelope with an upgraded floor has a high potential for energy saving. It is visible from the graph that an airtight, well-insulated building envelope with an improved floor construction in the month of January can decrease the heating use by 74% in case study building 1 and 82% in the case study building 2.

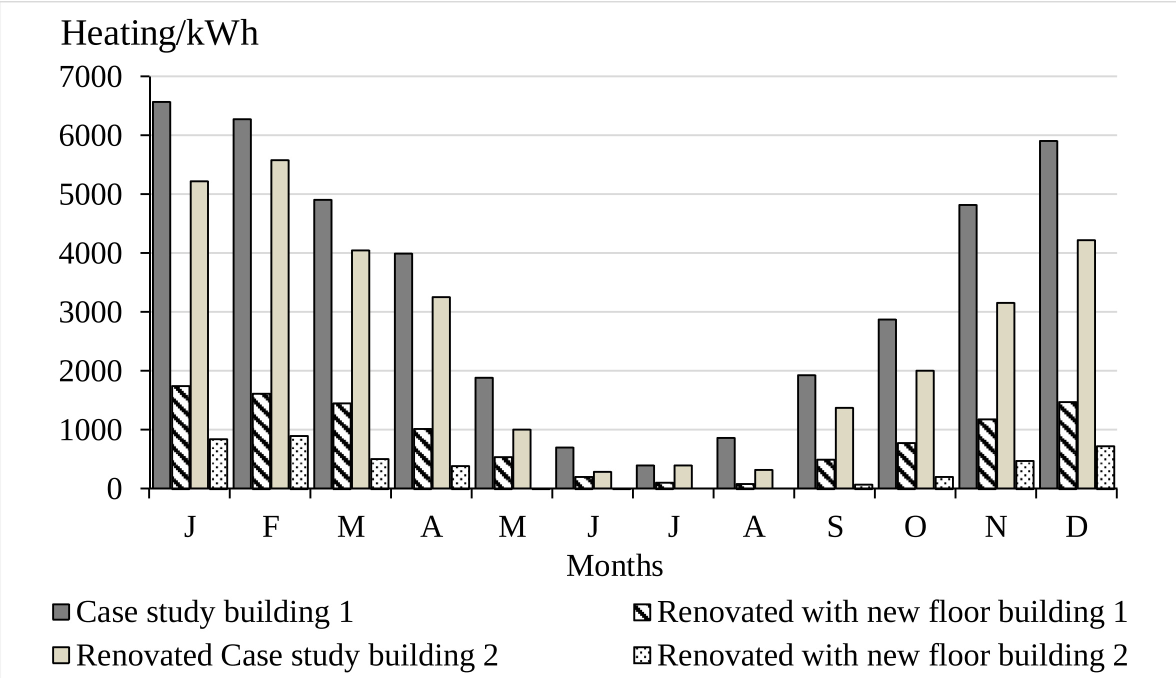

Fig 5.3: Heating use in existing and renovated case study buildings

Annual total energy reduction in case study building 1 and 2 is 30 MWh and 26 MWh respectively. Basically, it was an attempt to compare different phases of the building specifically before and after renovation. Because of the natural ventilation, all year round the required energy use is significantly higher compared to the improved external floor construction. It is a matter of fact that the heating use in the existing building and renovated building with improved floor cannot be compared since the corresponding ventilation systems are different. Therefore, the obtained simulation result will show higher reduction towards the heating intensity in the renovated floor case which is somehow misleading. For further analysis, the energy use in the renovated building and improved floor construction was performed, and it showed very low difference ranging between 5% to 18%. It indicates that without the addition of extra insulation on the floor the condition in the renovated building is substantially better. Although the graph shows heating demand during the warmer months because of the outdoor temperature variations. The software even takes into account minimum outdoor temperature for a specific day. This is one of the reasons for a lower heating demand during the warmer months. In reality, the building will not require any heating during the warmer months.

Another simulation was performed to see the optimum thickness of the insulation that could highly influence the heating energy intensity. The following graph shows the effect of insulation thickness on heating energy intensity. From figure 5.1 and 5.2, it was proved that additional insulation can contribute to energy reduction. Hence, simulations were performed to evaluate the impact of different insulation thickness on heating energy intensity. The graph showed highest energy intensity for heating when no insulation was added to the facade. It is true for both the case study buildings.

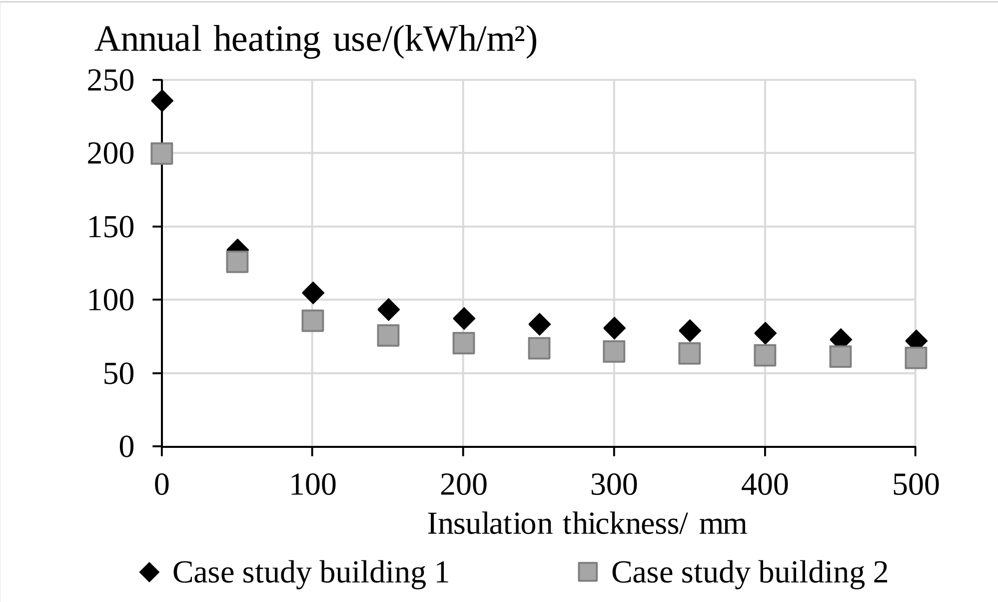

Fig 5.4: Impact of different insulation thickness (added outside of the facade)on heating use

The insulation increment shows a decreasing trend towards heating use. It is observed that the heating demand decreases marginally for insulation thicknesses up to approximately 400-500 mm. The biggest impact on the heating demand is observed when introducing the first 50 mm insulation to the walls compared to not having any insulation at all (Figure 5.4). The optimum insulation thickness is (250-300) mm for case study building 2 regarding heating use.

5.3 Heating use and heat loss in different parameters

Simulations were performed for heating use in each of the parameters and corresponding heat losses through the building envelope by various ways. It was mentioned earlier that thermal bridges were considered as 25% of the total building envelope for the base case.

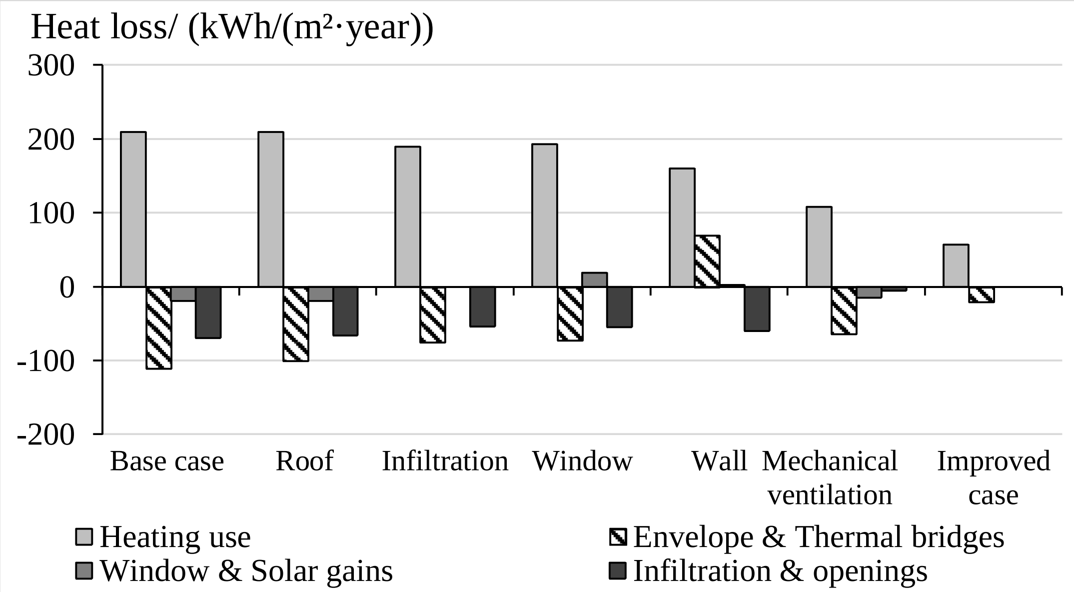

Figure 5.5: Heating use and heat losses through building envelope

Heat losses through the building envelope are plotted in X-axis, and heating use is plotted in the Y axis. The trend for heat loss showed a substantial decrease towards the addition of energy efficient strategies (see figure 5.5). The most influential parameter was mechanical ventilation system with heat recovery efficiency of 80%. The heat recovery efficiently reduced the ventilation losses by 32% accompanied by the improved airtightness and facade insulation. In addition to that, replacing the existing natural ventilation by mechanical ventilation can reduce the heat losses through infiltration and openings drastically.

Additional insulation on the external wall and roof can reduce the envelope losses by 36% and 34% respectively. In spite of replacing with triple pane windows the losses through infiltration and openings still exist due to the poor infiltration rate. By applying all of the renovation measures infiltration and thermal bridge losses can be minimized.

5.4 Thermal comfort analysis before and after renovation

The following figure shows the overheating hours before and after renovation for case study building 1 and 2 where FEBY schedule is applied. Different zones were plotted in the X-axis and the overheating hours were plotted in Y-axis. The overheating periods were determined by the operative temperature exceeding 25℃ and 27℃.

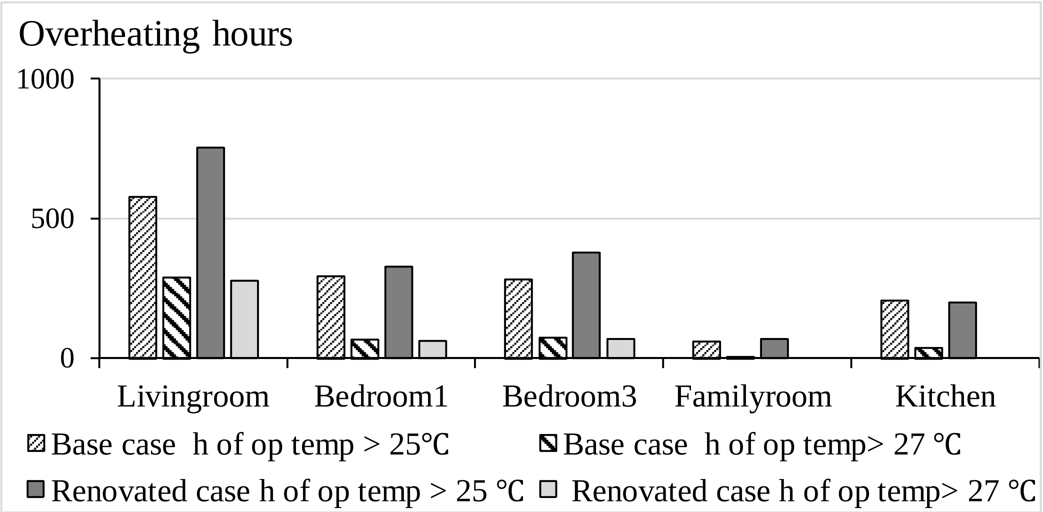

Figure 5.6: Overheating hours above 25℃ and 27℃ before and after renovation in case study building 1

Simulations were performed for assessing the overheating hours before and after renovation in case study building 1 and 2. The overheating hours were simulated with FEBY schedule for both of the case study buildings. As already mentioned in methodology section 5.1.2 that existing building is naturally ventilated. According to the result, the Livingroom and Bedroom have the maximum period of overheating. The living room has maximum 735 overheating hours when the temperature crosses 25 ℃. In the renovated building kitchen has approximately 200 overheating hours throughout the year. Family room being situated below ground level has the minimum heating hours among all other zones. It was observed that the overheating period in renovated building was 1.12 times higher in comparison with the existing building. It is due to the well-insulated and airtight building envelope which creates higher indoor temperature, especially during summer. It is important to mention that in this case the building was assumed airtight all the year round, no summer control was considered. The living room has large windows which can create draught during the winter season and excessive solar gains during summer because the windows are not energy-efficient. The replacement of energy-efficient windows with g-value of 76% did not contribute to the potential improvement of the indoor environment because no shading has been considered which can control the admission of daylight.

It is true that in summer the indoor thermal environment can be controlled by the occupant's preferences. Different shading devices were used to avoid the excessive solar gains so that it can bring significant reduction in the overheating hours and ensure a good thermal environment.

In case study building 2, Bedroom 3 and Bedroom 4 had the highest overheating period when the building was naturally ventilated. Studies show that occupants can tolerate a wide range of temperature in naturally ventilated buildings (Dear et al., 1997) due to behavioral and physiological adjustments.The simulation result for renovated building 2 is showing the similar trend like case study building 1. It is showing more overheating hours for an airtight and well-insulated building envelope. Similar to the case study building 1 this building was assumed airtight all the year round and no summer control (e.g. opening the window or doors) was considered. It is one of the reasons for too high temperature indoor.

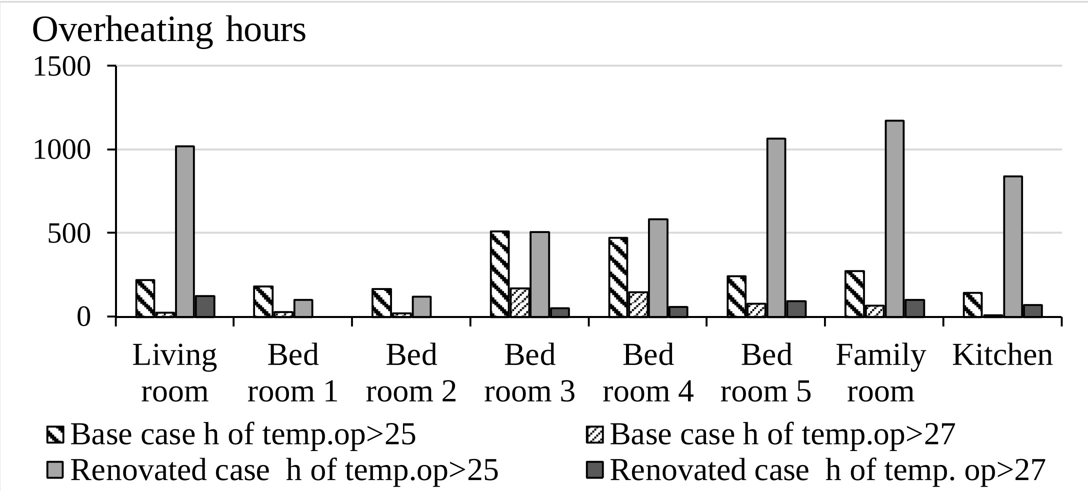

Figure 5.7: Overheating hours before and after renovation in case study building 2

The rooms situated at first-floor level (2.6m) had comparatively higher overheating hours in comparison with the rooms situated at ground level. Because the bedrooms situated on the first floor receives sunlight throughout the day and late afternoon as well especially in the summer and on the contrary, the facade is less exposed to sunlight on the ground floor. Since the room height is only 2.3 m at first floor level the direct solar gains on the roof added more heat to the indoor. The overheating period in bedroom 5 and family room in renovated building is three times higher compared to the existing building. In addition to that, the upgraded building envelope and the internal gains made the kitchen as one of the heated zone situated on the ground floor.

The simulation result was helpful to identify the potential problems in the zone which has more overheating hours. The overheating zones will be helpful for determining the actual thermal environment indoor.

5.4.1 Case study building 1

Afterwards, the variations in operative temperature between a naturally ventilated building and renovated building was assessed. Figure 5.8 presents the operative temperature in different zones for winter and summer period before renovation.

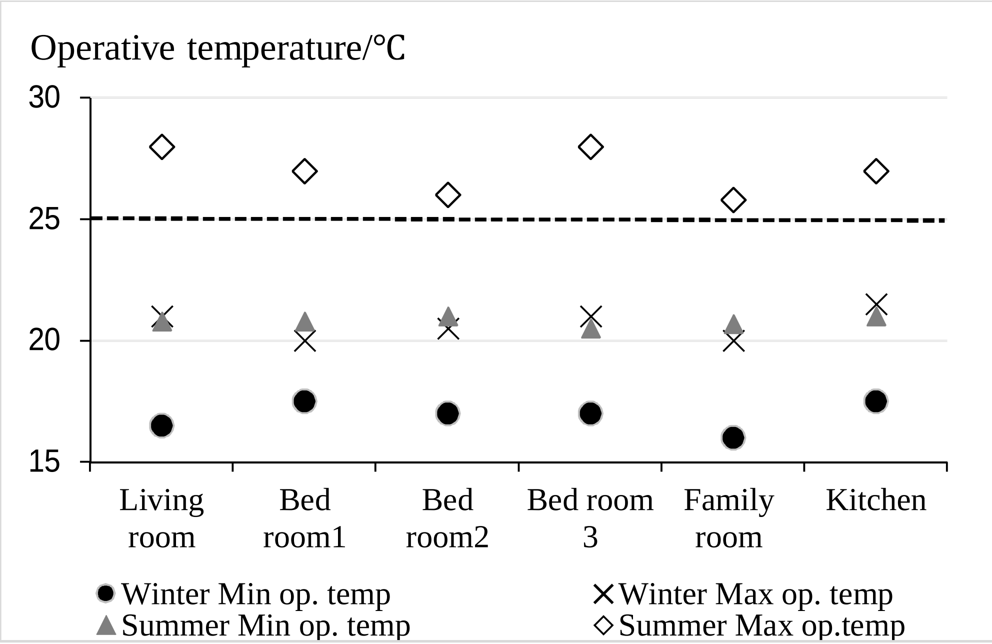

Figure 5.8: Minimum and maximum operative temperature in case study building 1 before renovation

The dotted line plotted on the X-axis is showing the threshold limit for operative temperature. Different lines show the minimum and maximum operative temperature in summer and winter period. The operative temperature was simulated with considering the heating system on during winter. As mentioned in an earlier section that the building envelope was poorly insulated and losses through the building envelope was high. The obtained result from simulation showed a minimum operative temperature of 16.5℃ and 16℃ in the living room and family room respectively during winter. The maximum temperature during winter season does not seem to have frequent fluctuations and ranges between 20 ℃ and 22 ℃. It was evident that the living room with large windows receives the maximum solar gains, and the simulated maximum operative temperature was 28℃ which makes the zone uncomfortable for the occupants. The operative temperature in Bedroom 3 reaches a maximum of 28℃ during summer. So, the temperature crosses the comfortable range. According to the ASHRAE standard stated in the methodology section 5.2.4, the optimum indoor temperature during winter in a naturally ventilated building should be minimum 21.3℃ or maximum 23.7℃. The minimum indoor temperature during summer should be 22.3 ℃ or maximum 24.7 ℃. The above standard is not met according to the simulations. It can be seen from the figure 5.8 that the winter operative temperature was much lower in this case. While, on the other hand the summer temperature was much higher. Figure 5.9 presents operative temperature in different zones for winter and summer period after renovation.

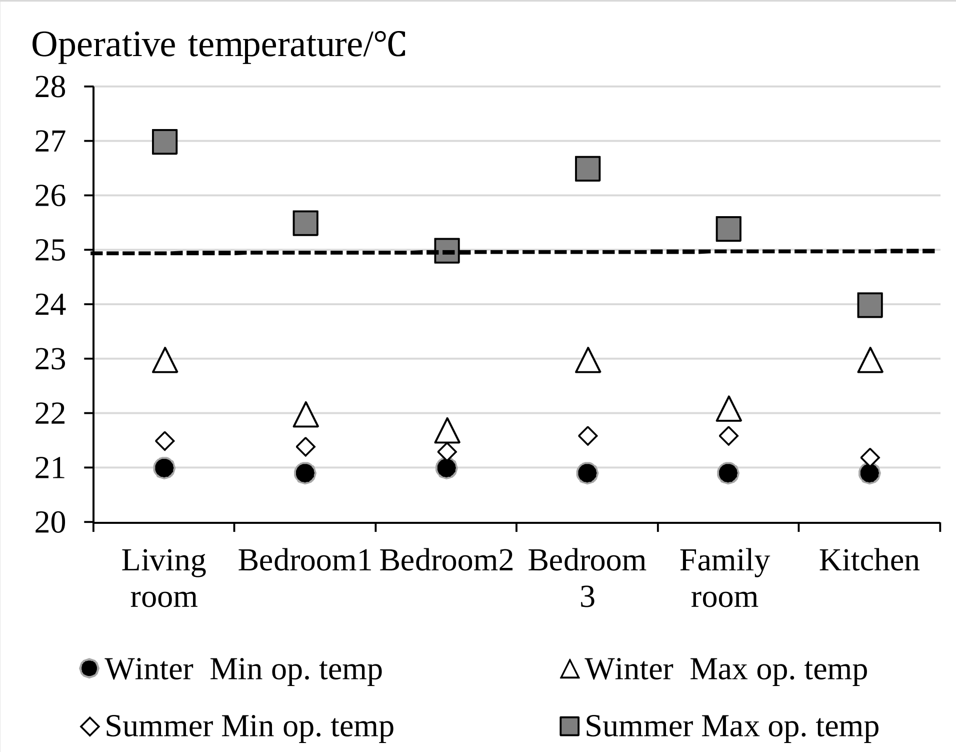

Figure: 5.9: Operative temperature in case study building 1 after renovation

The dotted line plotted similarly, as Figure 5.8 showing the threshold limit for operative temperature 25 °C. It is important to note that the radiators were considered on during the winter. The airtight building envelope helped to maintain constant higher values for operative temperature during winter. The operative temperature during winter was approximately 21°C for all of the zones plotted in the graph. It can be seen that the maximum temperature in winter can increase up to 23°C. The triple pane windows minimized the excessive solar gains on the southwestern facade, and the operative temperature was reduced by only 1°C in the Livingroom compared to the base case. It is because no external shading was considered in this case. According to the graph the operative temperature can rise up to 23°C during winter at the kitchen and living room. The electrical equipment and lightings were considered as energy efficient not to generate too high temperature indoor. As stated in the methodology section (equation 4 and 5) the comfort temperature in Livingroom's and the kitchen is 21.06 °C during winter and 22°C during summer. In both of the case, the external reference temperature should be lower than 12.5 °C during winter and higher than 12.5 °C during summer. On the basis of equation 5 and 6, there exists upper and lower limit for the comfort temperature. The upper limit and lower limits are 24.5 °C and 20.5 °C respectively. However, according to the graph the operative temperature exceeded 25°C in the living room so the comfort temperature cannot be achieved on this particular occasion. For bedrooms, the standard comfort or neutral temperature is 16°C during winter (if the external temperature is below 0 °C). The operative temperature in Bedrooms during winter is 21 °C which is higher in comparison with the standard. The standard for comfort temperature during summer was not taken into consideration due to the discrepancy regarding the comfort temperature. Moreover, it can be seen that the operative temperature does not go beyond 21°C in the renovated building.

The following table shows the glass type and shading considered for case study building 1 after renovation. The overheating hours were considered when the temperature exceeds 25 °C and 27 °C respectively.

Table: 5.3: The glazing and shading type considered for case study building 1 after renovation

	Glass type	Shading device	U-value without shading/ (W/(m²·K))	U- value with shading/ (W/(m²·K))
1.	3 mm low-emissive glass	Interior roller blind	1.53	1.27
2	Triple-glazed with low-e film	Exterior screen	1.12	1.08
3.	Triple pane glass with suspended low emissive film	External venetian blind with schedules	1.12	1.01

Figure 5.11 and 5.12 presents the overheating scenario for different shading devices simulated for case study building 1.The building has a few overheated zones compared to case study building 2. From figure 3.2 it can be seen that the layout consists of different zones and is segregated by a common space. The heated air from inside can pass through the hall way. This is one of the reasons that case study building 1 has few overheated hours. Figure 5.10 shows the living room with and without shading device. The exterior screen was simulated as one of the shading devices to see the impact on reducing the overheating hours.

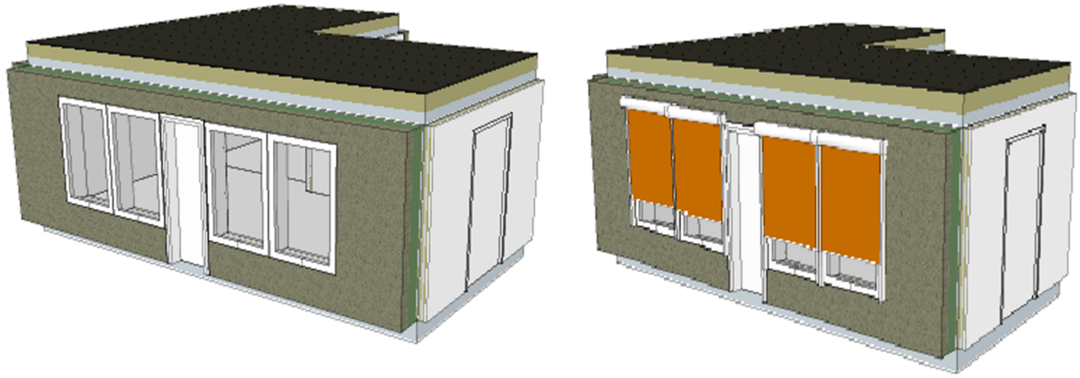

Figure: 5.10: The living room in case study building 1 with and without shading

The living room has approximately 753 hours of the overheating period without any shading. As can be seen (Figure: 5.11) addition of an external Venetian blind reduced the overheating hours in the living room by 72%. The graph shows that exterior screen can reduce the overheating period drastically by 78% in bedroom 1. The external Venetian blind efficiently reduced the overheating hours in both of the bedrooms as plotted in the graph. On the contrary bedroom, 3 being situated in the southwest has a reduction of 58%. These zones were further stimulated with external Venetian blind controlled by the sun and specific schedules and it reduced the overheating hours drastically by 94% in bedroom 1 situated towards Southeast. In addition to that the shading device showed a reduction in overheating hours by 72% and 51% respectively in the living room and bedroom 3. It was difficult to minimize overheating hours in the rooms especially situated towards the southwest. There still exists around 200 hours of the overheating period in the living room and 160 overheating hours in Bedroom 3.

It is noticeable that the thermal comfort level in the existing building is at a risk because the temperature level in the specific zones exceeded 27°C. The exterior screen minimized the direct solar gains in a southeast oriented Bedroom 1. But as a matter of fact, there exists few overheating hours in the living room and Bedroom 3 although exterior screen has been applied to minimize the solar gains during summer.

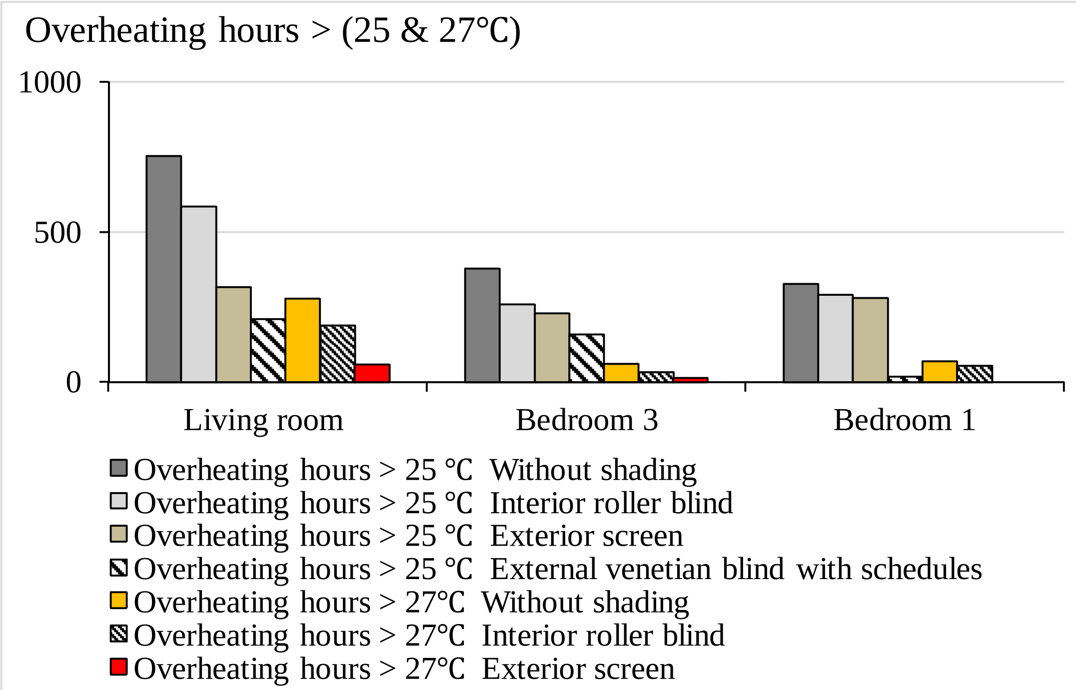

Figure: 5.11: Overheating hours above 25°C and 27°C for different shading devices after renovation

Finally, the Venetian blinds with a specific summer control schedule were simulated for Living room and Bedroom 3, and it successfully reduced the overheating hours in this specific zones. Schedules were applied by analyzing the sun path diagram. The time for each facade receiving maximum sunlight was assumed that helped to build up the schedule.

Being one of the worst zones in terms of overheating periods Livingroom was chosen for further analysis on thermal comfort. To assess the thermal environment simulations were performed throughout the year. So, one representative day from each season were chosen for the study. Since the living room has large windows, it was important to see if it is possible to achieve a desired comfortable indoor environment by upgrading building envelope and adding external shading. Simulations were performed for four days such as 21st March, 21st June, 21st September and 21st December.

The trend of operative temperature for 21st June started to rise slowly and continued until it reaches the peak of 25°C. It is observed that the temperature seemed to have a very flat trend during December throughout the day and increased slightly during the evening hours due to the internal gains and equipment loads. During September, the operative temperature ranges between 21.8°C and 22.5°C.

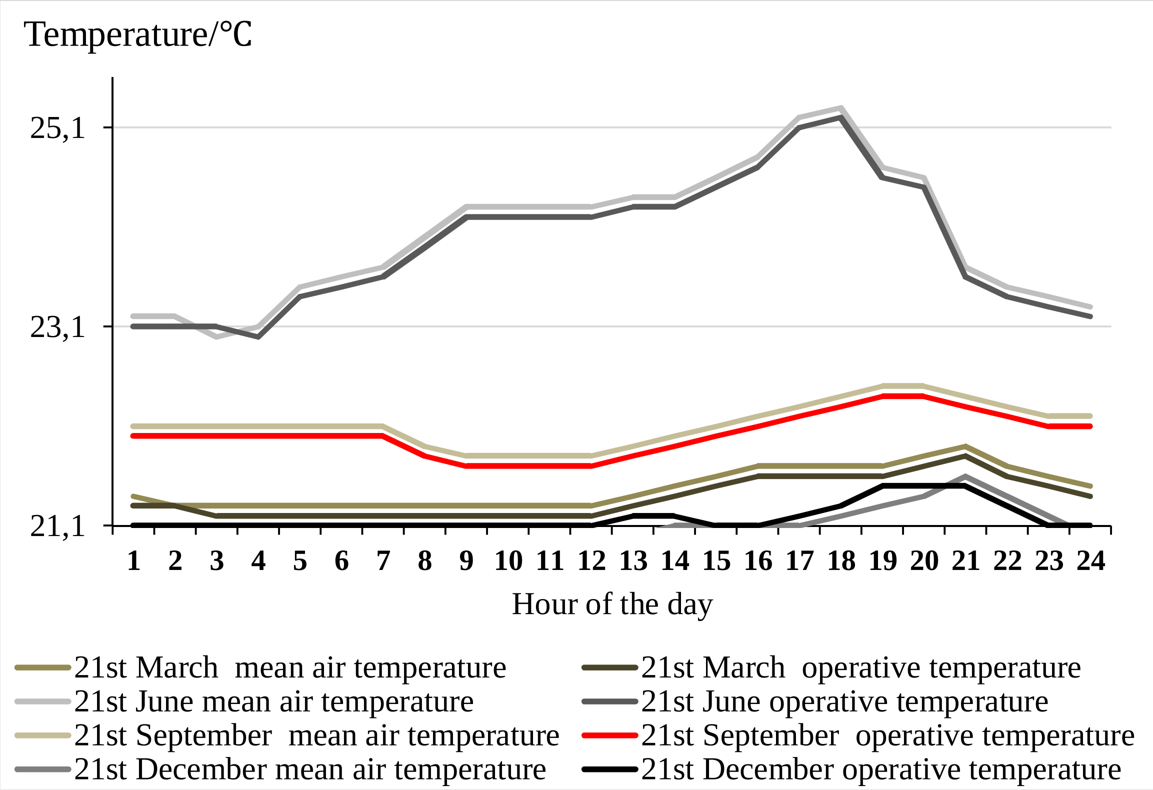

Figure: 5.12: Hourly mean air temperature and operative temperature in the living room after renovation

It is noticeable that neither of the zones exceeded the comfortable range. During winter the lowest temperature can be seen from the graph was 21.1°C. According to the equation 4 and 5 the upper limit for a comfort band is 24.5°C. The graph showed that during the afternoon hours between 15.30 pm and 17.30 pm the temperature crossed the comfort region but afterwards decreased considerably to the level of 23°C.

After obtaining the results for operative temperature with shading for a southwest oriented living room, the PPD for the corresponding days were investigated to see if a comfortable indoor environment can be maintained in different seasons. The hourly values were simulated because it gives precise results in terms of temperature or PPD variations.

Figure 5.13 shows the PPD analysis for corresponding days as mentioned in the previous graph. Although the shading is considered on between 15th May and 15th September. To avoid any overheating scenario shading has been considered during the simulation for fall equinox i.e. 21st September. It lies with the expected PPD in the living room during summer showing an increasing trend which crossed the limit of 10% as can be seen from the graph. In this case, the maximum PPD is 10.3.

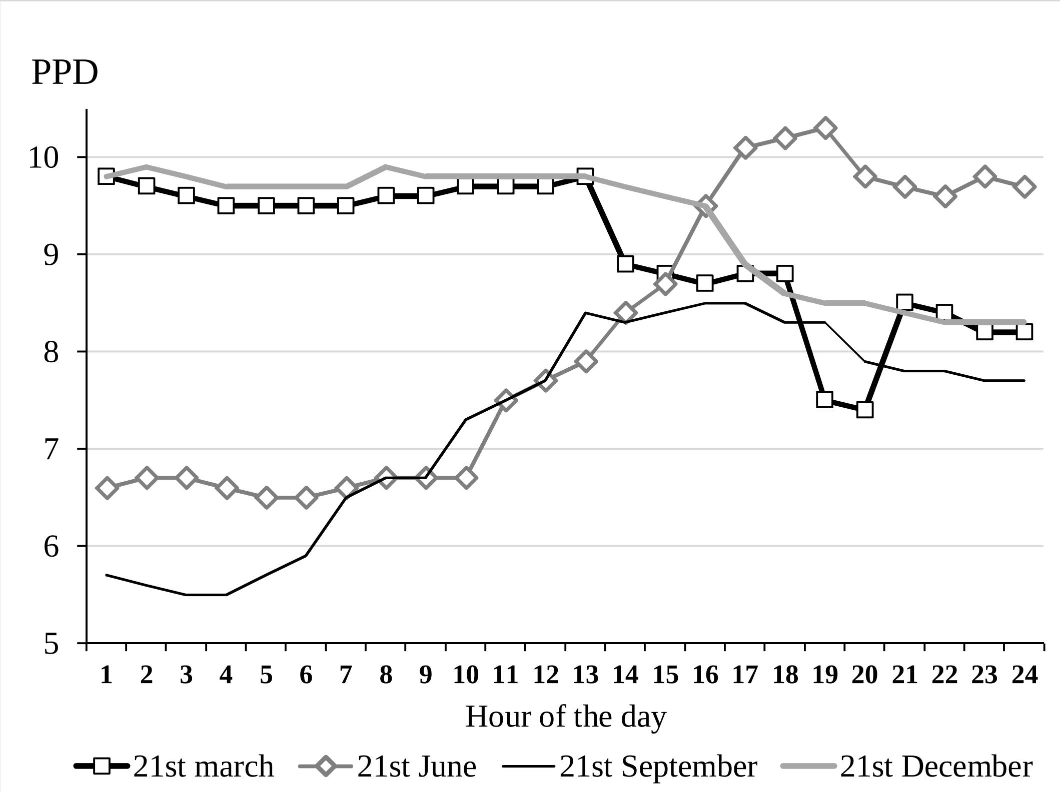

Figure 5.13: PPD analysis in the living room for four different day after renovation

The operative temperature in figure 5.12 did not seem to cross 25℃ for too long. But as a matter of fact, occupants will feel uncomfortable for the PPD being higher than 10. The trend line for September showing a moderate variation in the PPD level and ranges between 5 and 8. However, during March, a steady condition was noticeable which was followed by a level drop to 7.5%. According to ISO-7730 and Miljöbyggnad the minimum value for thermal dissatisfaction is 5%. Figure 5.13 shows that the trend for the corresponding days does not go below the minimum dissatisfaction range i.e. is 5%.

Besides Livingroom, it is important to assess the thermal comfort conditions in the Bedrooms. The simulations were performed with the external shading. Two bedrooms situated towards southwest and south-east were chosen in this case. The graph shows hourly temperature simulated on a typical summer day 21st June.

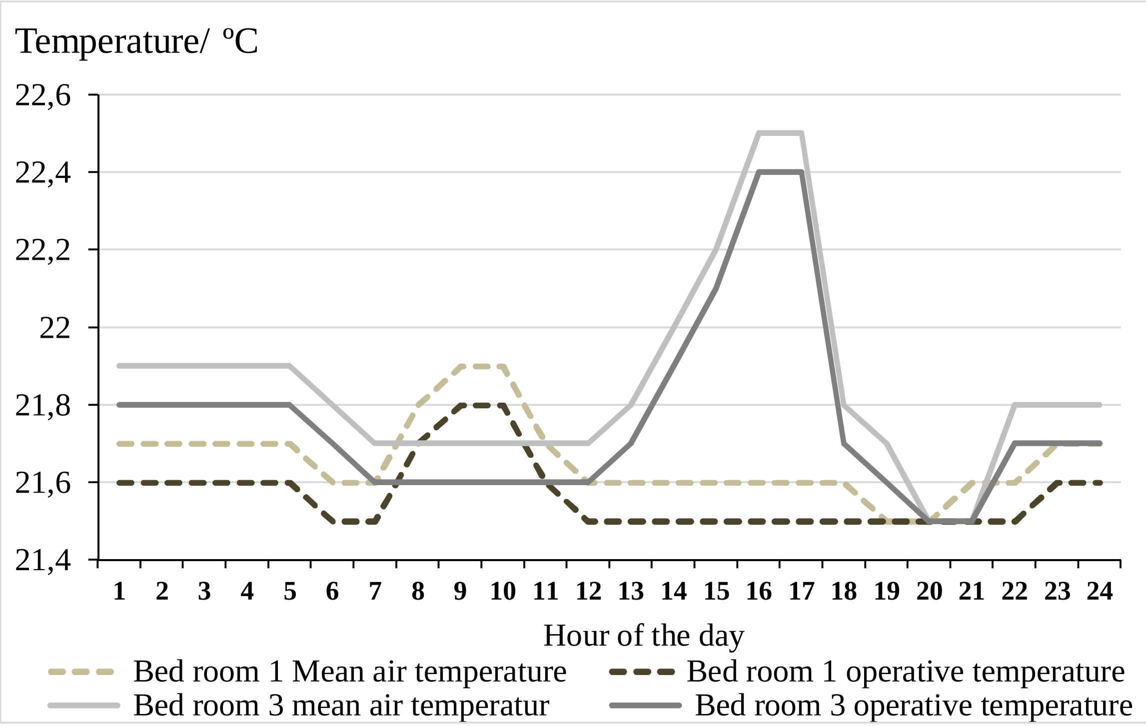

Figure: 5.14: Simulated hourly operative temperature in bedroom 3 and bedroom 1 in the renovated building with external shading

The bedroom is occupied between 22:0 pm and 7:00am. The operative temperature in bedroom 3 located in the southwest showing an increasing trend towards the afternoon hours and starts to decrease towards the evening hours. During the afternoon hours specifically in between 16:00 pm and 17:00 pm the operative temperature reached the peak of 22.5°C. The west facade accumulates heat during the afternoon hours, as a result it can give rise to the operative temperature. However, in line with the expectations the operative temperature in bedroom 1 showing moderate variations throughout the day. The operative temperature reached at the upper limit of 21.9 °C in the morning hours between 9 am till 11 am. It is because the room receives the solar gain during the morning hours for being situated towards the southeast. The rest of the day the operative temperature exists in the region of 21.6°C. Therefore, it can be concluded that the indoor thermal condition in bedroom 1 is comparatively better than bedroom 3. The operative temperature was evaluated for three typical summer days from June, July, and August.

After the simulations had been performed for summer, it was important to evaluate the condition during winter. Simulations were performed for a typical winter day after renovation. Previous figure 5.14 shows a typical winter weekend simulation. So in case study building 1 simulations were performed for a typical winter weekday 21st January, when the outdoor temperature varied between -3 °C and +0,3 °C.

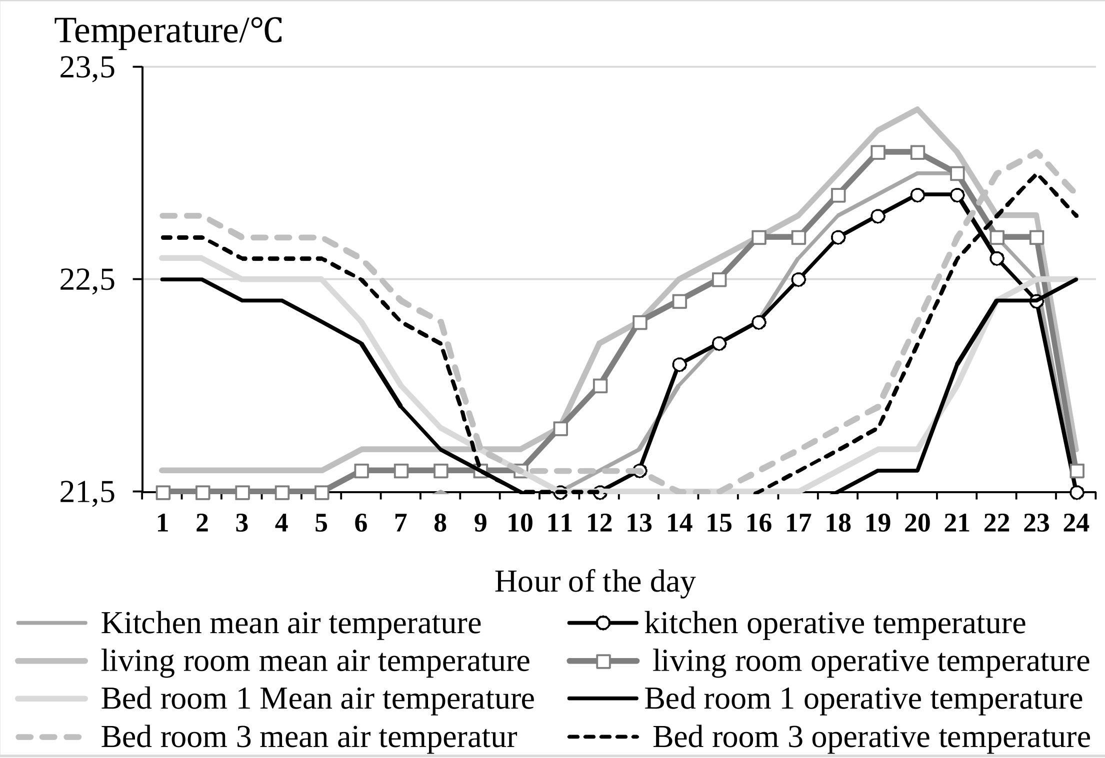

Figure 5.15: Hourly temperature in living room and kitchen simulated on 21st January in the renovated case study building 1

Simulations were performed for three different orientations such as northeast, southeast, and southwest. The zones showing a slow increase towards the evening hours especially in the Livingroom and kitchen and also started to decrease after the occupied hours. The occupants were considered present in the corresponding rooms while simulating. Occupant's position was considered 1m from the facade. The amount of sunlight during winter is generally low and being situated in the northeast the zone receives a negligible amount of solar gains. This is why the operative temperature has a trend line very similar to the mean air temperature. The temperature continually rises in the proceeding hours and reached the highest point of 23.3°C for the living room during the evening. It is due to the metabolic heat exchange of the occupants, and heat generation from the lighting and equipment. The operative temperature started to decrease soon after the occupants leave the zones. The scenario for bedrooms is showing a different trend. During the occupied hours from 10.00 pm till 7.00 am the temperature was comparatively higher and decreased considerably towards the morning hours. The trend stabilized during the day, and an increasing trend is noticeable in the late evening hours. The maximum temperature for Bedroom 1 and Bedroom 3 is 22.5 ℃ 23℃. The upper limit for bedroom 3 is surprisingly showing higher temperature although the equipment load is very low compared to Livingroom and kitchen. The reason for temperature variation in the renovated building mainly due to the heat generated activities in the kitchen or living rooms.

5.4.2 Case study building 2

After the analysis for case study building 1, the following information is presented for case study building 2.

Table 5.4: The glazing and shading type considered for case study building 2

	Glass type	Shading device	U-value without shading/ (W/(m²·K))	U-value with shading/ (W/(m²·K))
1.	Double pane low emissive glass	External blind	1.75	1.5
2	Triple pane clear glass	Interior roller blinds	1.86	1.57
3	Triple pane suspended low-e-film	Exterior venetian blind with schedules	1.12	1.01
4.	Venetian blind between two panes	-	0.91	0.83

Case study building 2 has more overheated hours in comparison with case study building 1. It is due to the orientation of the building which makes it worst in terms of heating hours. Besides, simulations were also performed in online software Casanova to determine the amount of solar gains throughout the year. For further queries regarding the solar gains please check Appendix C.

The following figure shows the difference in overheating hours for each of the simulated shading types.

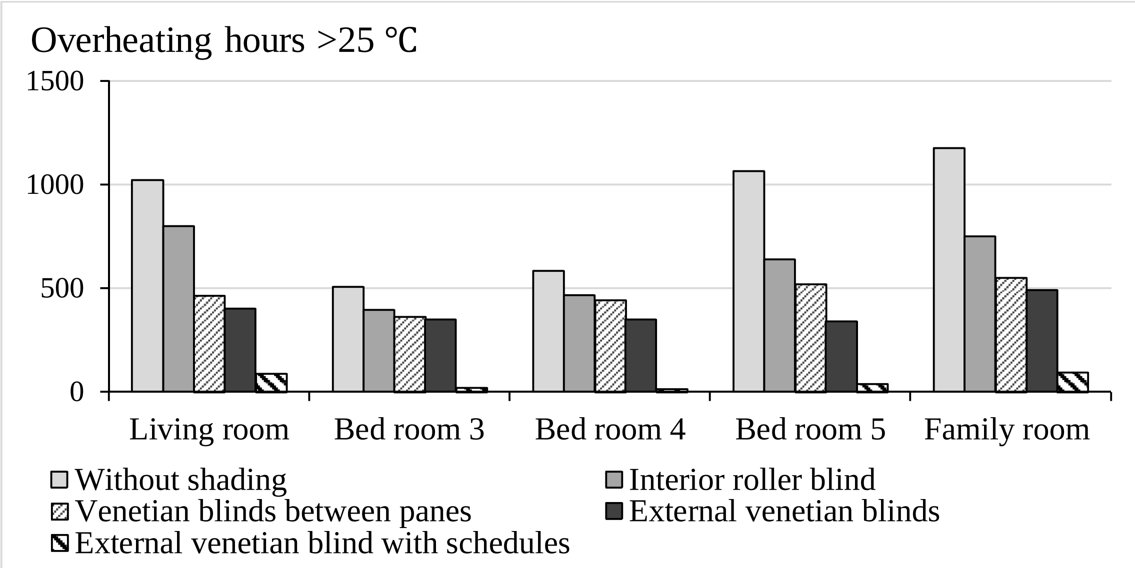

Fig 5.16: Overheating hours above 25 ℃ for different shading devices in the renovated case study building 2

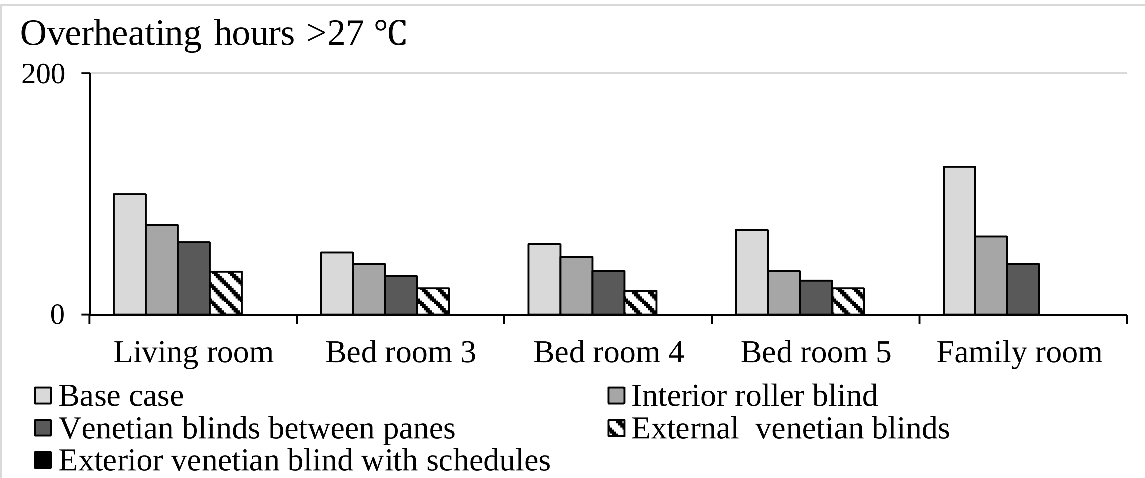

Fig 5.17: Overheating hours above 27℃ for different shading devices in case study building2

The result of the shading analysis showed a maximum reduction of 88% in overheating hours for living room and family room situated towards southwest (Figure 5.17). A specific schedule for the external Venetian blind was made for each of the orientation by analyzing the sun path diagram. The control system was chosen as sun and schedule. It was one of the efficient shadings in terms of minimizing the solar gains. It was considered to minimize the overheating hours especially in the zones suffering mostly from the overheating periods. In addition to that external Venetian blinds reduced the overheating hours by 70% and 58% in both living room and family room (see figure 5.17). It shows that (figure : 5.17) overheating hours does not exceed 27°C in all of the zones if external Venetian blind with the schedule is applied as a shading.

To get a standard overview for the overheating hours, the equipment heat gains were considered according to the FEBY schedule. To make the calculations simple stochastic approach was not considered in this particular section. Simulations were performed for a typical summer month to determine the comfort condition in the living room and family room. As figure 5.16 and 5.17 shows reduction in overheating hours after the installation of exterior Venetian blinds with the schedule, the following graph shows the impact of shading device indoor. The mean air temperature and operative temperature were plotted for a typical summer month (June) for two corresponding rooms.

The temperature fluctuations are comparatively higher in the family room. Solar gain is creating discrepancies between the two zones namely as the living room and family room. The living room situated towards the southwest at ground level receives comparatively less sunlight compared to the family room. Being situated on the first-floor level the solar gain is higher in the family room. The temperature reached the maximum of 25.4 °C during the middle of the month and stabilized for a couple of days as can be seen (Figure 5.18). The lower limit for the living room and the family room was 21°C and 21.6°C respectively.

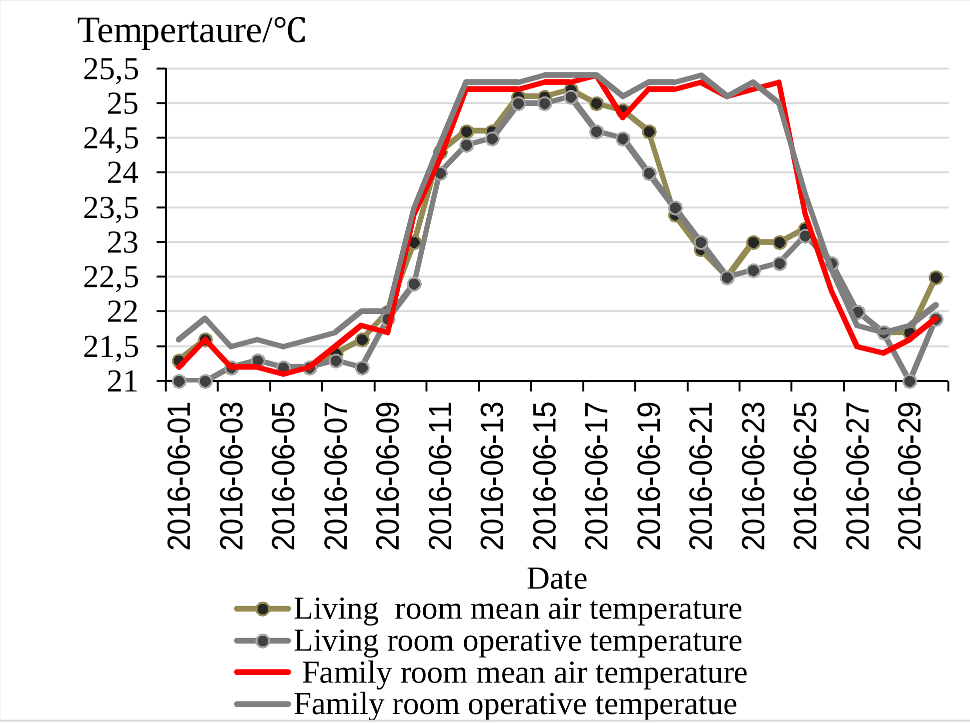

Figure: 5.18: Monthly summer temperature for living room and family room in the renovated case study building 2

The operative temperature in the living room showing an increase by 25℃ for three consecutive days during the middle of June. However, the scenario is much worst in the family room. The operative temperature stayed for a couple of days at 25.4 ℃ and followed by a drastic temperature drop by 21.7 ℃. It can be seen that the operative temperature in the family room exists around 25.4 ℃ for eight consecutive days which made the zone as one of the most heated zones during summer. However, to avoid unnecessary error, the roof is considered flat. Since the room height is only 2.3 m, the direct solar gains on the roof can easily add more heat to the indoor. However, it is worth mentioning that since these two zones were the most problematic zones in terms of solar gains, the external Venetian blinds with schedules have kept the temperature within 25.4℃. But according to the upper limit of comfort temperature requirement, the living room and family room could not satisfy the specific criteria.

Further results regarding the PPD is presented below. It was important to investigate whether the two zones with higher temperature has the similar effect on PPD.

Table: 5.5:Predicted percentage of dissatisfied during summer

	PPD	June	July	August
Living room	Min	5.4	5.4	5.3
	Max	10.1	9.4	9.9
Family room	Min	5.3	4.9	5.2
	Max	10.3	10.5	10.2
Bedroom	Min	5.4	5.1	5.2
	Max	9.8	9.6	9.9

Table 5.5 shows the occupant's dissatisfaction regarding the indoor environment. According to the table 4.7 described in the methodology, the PPD values for each zone should be below 10 to obtain a level for gold rating in Mijöbyggnad. The percentage of dissatisfied is slightly higher than 10 in the family room during summer. The dissatisfaction percentages for bedroom 5 exists around the ideal numbers which in this case less than 10% and obtained Miljöbyggnad gold. In addition to that living room has PPD slightly higher than 10 in June while the condition is ideal for July and August.

Since the summer condition was investigated for the most overheated zones, it was necessary to perform further simulations for winter condition. The thermal comfort can vary in different zones due to very low solar gains during winter. Another issue will be investigated whether the more airtight building envelope results in higher temperature indoor in winter. The main concern was to evaluate the thermal comfort condition in living rooms and bedrooms where people spend most of the time. It was important to assess the thermal comfort of the rooms situated towards the northeast. As a matter of fact, northeast is equipped with the service zones such as laundry and washrooms and are equipped for a very short time period. Therefore, thermal comfort condition was not investigated for northeast orientation in case study building 2. Figure 5.19 shows the hourly temperature of three zones such as living room, family room and bedroom 5 for a typical winter day simulation.

Different hours of a typical winter weekend is plotted on the X-axis, and the temperature is plotted on the Y-axis. The simulation was performed for a typical winter weekend. There are no specific criteria for weekends in FEBY 12. So, a typical weekend schedule was developed by the author. Simulations were performed for a typical winter weekend in comparison with the weekday schedule because there exists variations in internal gains, occupancy and lighting.

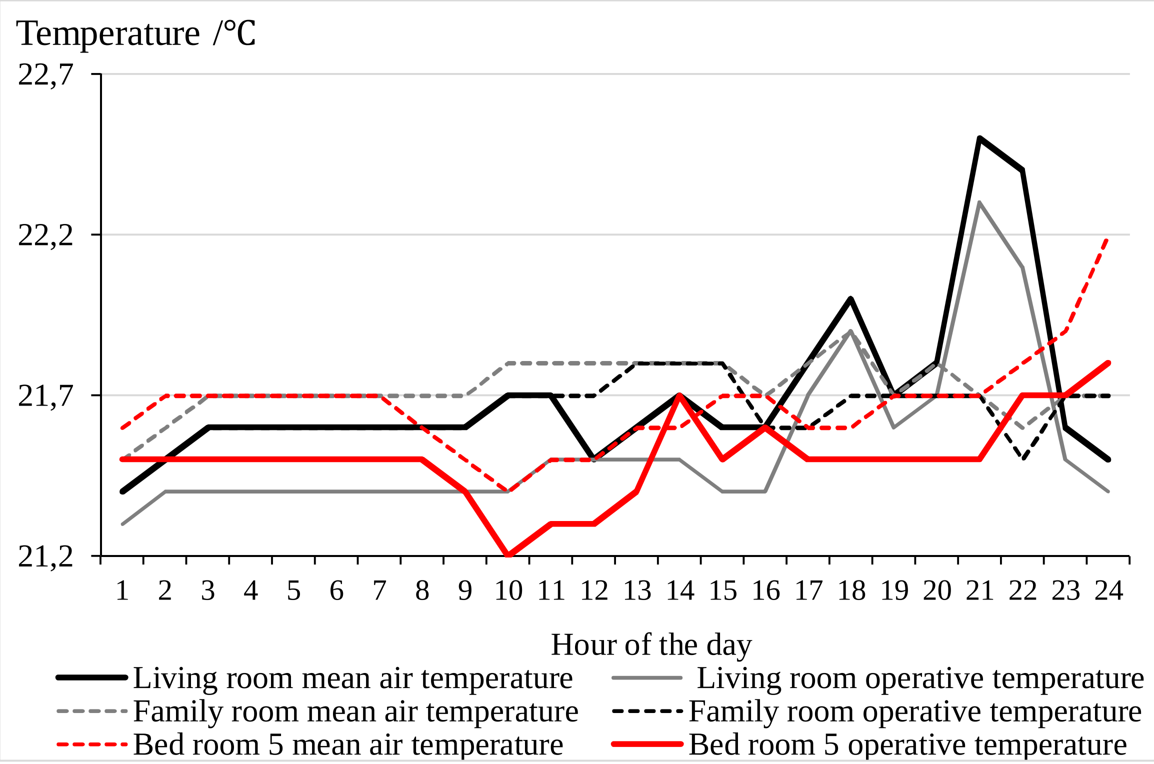

Figure: 5.19: Hourly temperature in living room, family room and bedroom 5 during winter after renovation

The occupants were considered present in the living room except from 14:30-16.00 pm. The family room is also showing the similar trend like living room except in the evening hours as the occupants are considered not present. The overall trend for each of the zones showing temperature variations precisely for each of the hour depending on the occupancy and internal gains. Although the graph showing very small temperature fluctuations but the zones did not cross the comfortable range. Water based radiator was used for the heat supply in each of the zones and was constantly on in this occasion. The trend for operative temperature seemed to decrease in the morning hours and increased slowly in the proceeding hours until it reaches the maximum of 21.7°C in the Bedroom 5. The operative temperature in the living room starts to increase slightly and remains between 11am until 14 pm due to the presence of occupants. An ascending trend for temperature is noticeable during the late evening hours especially in the living room. The temperature in the living room reaches 22.4 °C during that period. Equipment load, lighting and internal gains from the occupants gave a rise to the temperature. During winter, the comfort temperature in the bedroom according to equation [2] is 16°C. In case study building 2, the trends line hovers around 21°C. So, the simulated result was showing higher temperature in comparison with equation 2. The living room and family room exists within the range of comfort temperature.

The following table presents the monthly PPD values for winter.

Table: 5.6: Predicted percentage of dissatisfied during winter

	PPD	Dec	Jan	Feb
Living room	Min	7.5	7.5	8.4
	Max	9.8	9.7	9.7
Bedroom 5	Min	6.6	7.7	8.4
	Max	9.4	9.7	9.5
Family room	Min	7.5	7.5	8.2
	Max	9.8	9.6	9.8

The maximum PPD for family room increased up to the level of 9.8 during December and January. But the range did not cross the limit of 10%. The corresponding PPD value for each of the specified zone exists within the acceptable range. Looking at the individual zone it can be seen that the PPD index does not have high fluctuations. The rating Miljöbyggnad 'Gold' can be obtained for each of the zones during winter.

5.4.3 PPD analysis before and after renovation of both the buildings

The figure 5.20 shows the monthly PPD before renovation in case study building 1. The graph shows higher PPD during the heating season, and the trend tends to decrease as the outdoor temperature increases. Due to the poor building envelope, the higher infiltration rate increased the heat loss and therefore the indoor temperature went below the comfort range. To keep a constant air temperature during the heating season, the building envelope requires high energy use.

The simulated occupancy was scheduled as present during the summer to control the excessive solar gains through windows. The result shows the PPD range for the living room and bedroom slightly higher than 10 which corresponds to PMV approximately 0.5 which is within the recommended limits (-0.5< PMV<+0.5) during summer. It is considered as uncomfortable for the occupants.

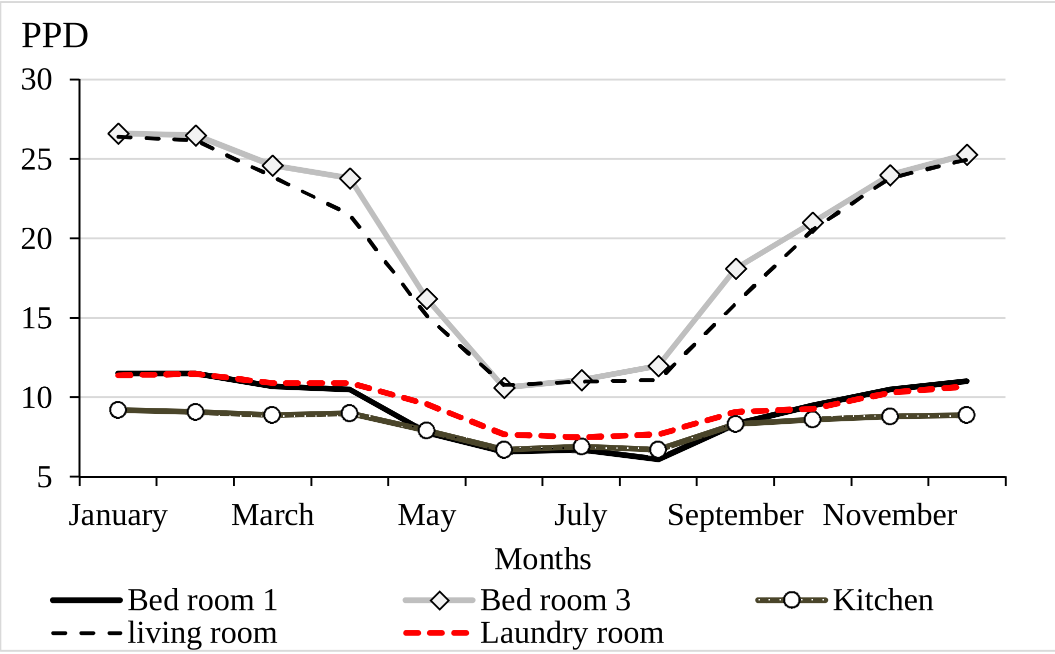

Fig 5.20: Predicted Percentage of Dissatisfied in case study building 1 before renovation

Several study reveals that PPD index is not a reliable indicator to determine discomfort level in a naturally ventilated building (Dear et al.,1997). It shows an assumption for comfort zone where no thermal dissatisfaction can occur. But in reality, people can feel discomfort at any temperature (Nicol et al., 2008). It implies that only higher temperature is not solely responsible for thermal discomfort. According to the result, kitchen is a comfort zone with no thermal dissatisfaction throughout the year. The simulation result showed that people will not be dissatisfied in the kitchen during summer although the maximum temperature reaches above 25℃.

The figure 5.21 shows the PMV distribution for assessing the thermal comfort condition of the occupants in case study building 1 which is naturally ventilated.

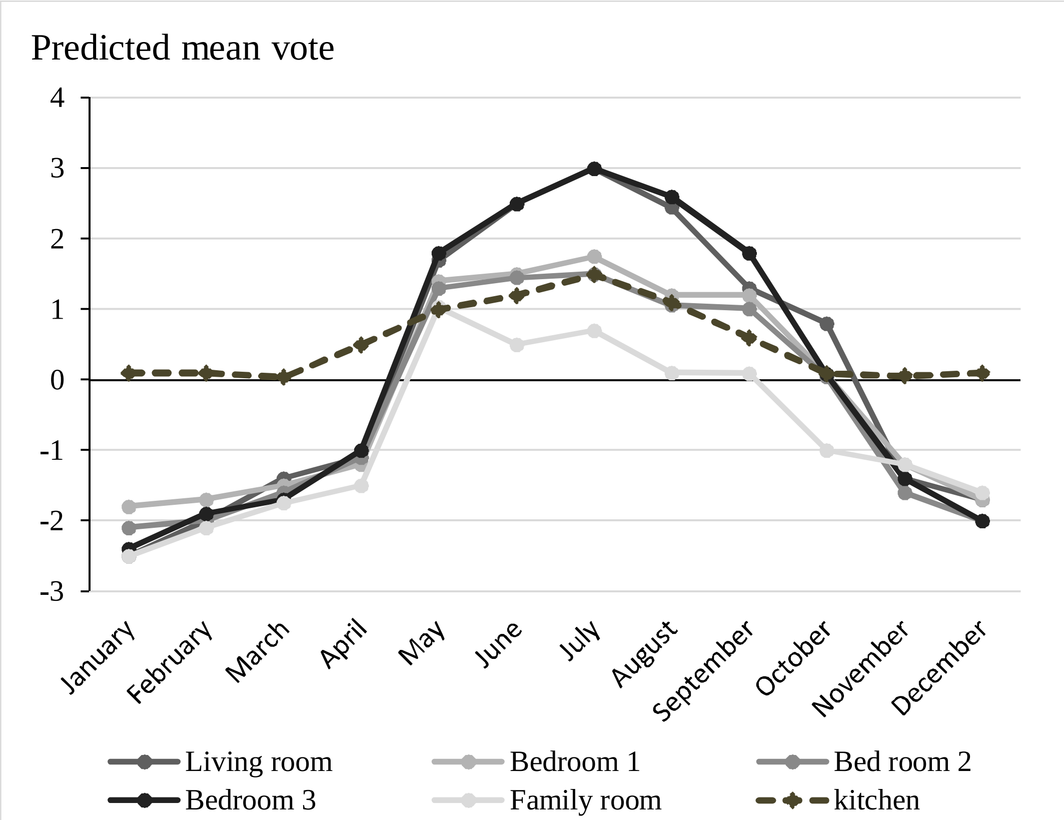

Figure 5.21: Distribution of Predicted mean vote throughout the year in case study building 1 before renovation

The X- axis is showing different months of the year and Y-axis showing the index for PMV. The PMV range is between -3% and +3% that is true for the existing building because the PPD range was more than 15%. Clothing level was also taken into consideration based on the different seasonal preferences. From the figure it can be seen that the graph shows very high cold sensation in the family room, living room and bedroom 3 during the heating season. It is evident that these zones have minimum operative temperatures during the heating season (see figure 5.21). Therefore, it showed a direct relationship between the operative temperature and PMV index. The PMV curve showing an increasing trend towards the warmer months and reached its peak during July especially for bedroom 3. Different zones are showing the similar PMV trend except the kitchen. It shows an unrealistic value regarding the PMV index for the kitchen which cannot be true for whole year simulation period.

The PPD and PMV index in a naturally ventilated building accounts for thermal adaptation to a certain extent .The summer and winter comfort zone instruction is not appropriate for this specific model. It provides strong evidence for not selecting the PPD and PMV as a medium of thermal comfort prediction in naturally ventilated buildings.

The following figure shows the monthly PPD values before renovation in the case study building 2

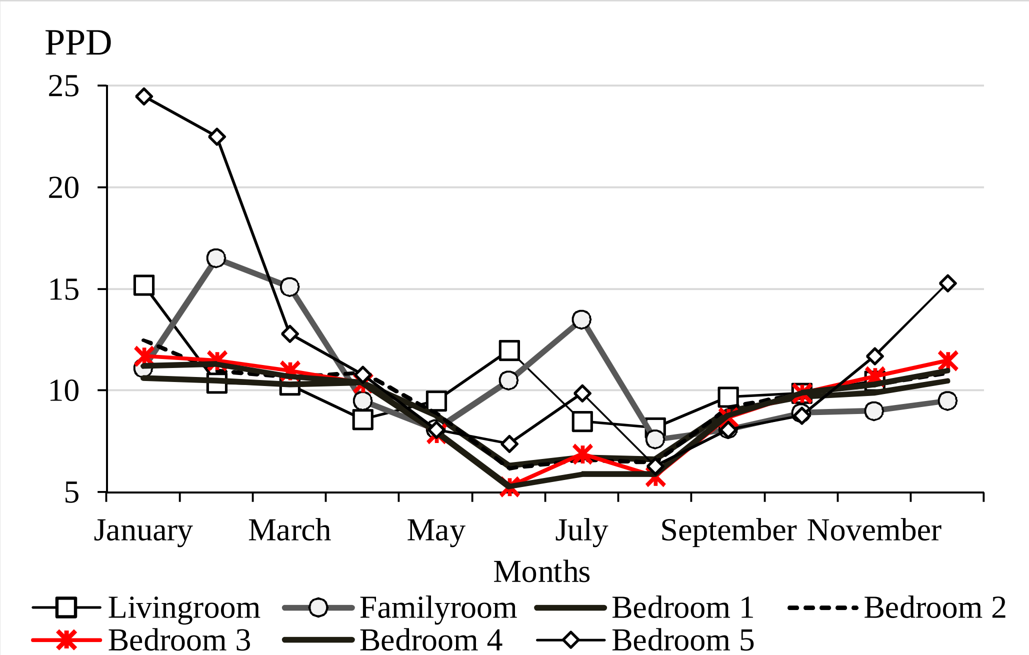

Figure: 5.22: Predicted percentage of dissatisfied in case study building 2 before renovation

The trend showing a similar scenario to some extent as case study building 1. The building is naturally ventilated which shows higher PPD level during the heating season and starts to decrease during the summer period. Bedroom 5 and familyroom showing the maximum PPD of 24.5 and 16 during winter. During summer, the PPD level reaches by 13.5 and 12 respectively in Livingroom and family room. The bedrooms situated towards northwest on the ground and first-floor level has almost the same configuration. It can be seen that the trend line for bedrooms overlapped with each other. It is because the obtained PPD value for each of the month is close to each other for the similarly configured rooms. It can be seen that the PPD level in all of the zones is higher than 10.

To determine the existing thermal condition in the renovated building the analysis for each specific zone is necessary. Seasonal change can also influence the thermal environment indoor. It may be difficult in terms of maintaining a comfortable environment in few zones during summer but can be adequately comfortable in winter. So, the simulations were performed for typical summer and winter weeks. On this occasion PPD index has been analyzed to determine the influence of renovation measures on the thermal comfort level of the occupants. The graphs from 5.23 to 5.28 presents the indoor thermal condition in two of the case study buildings.

The graph shows the PPD index in the renovated case study building 1.

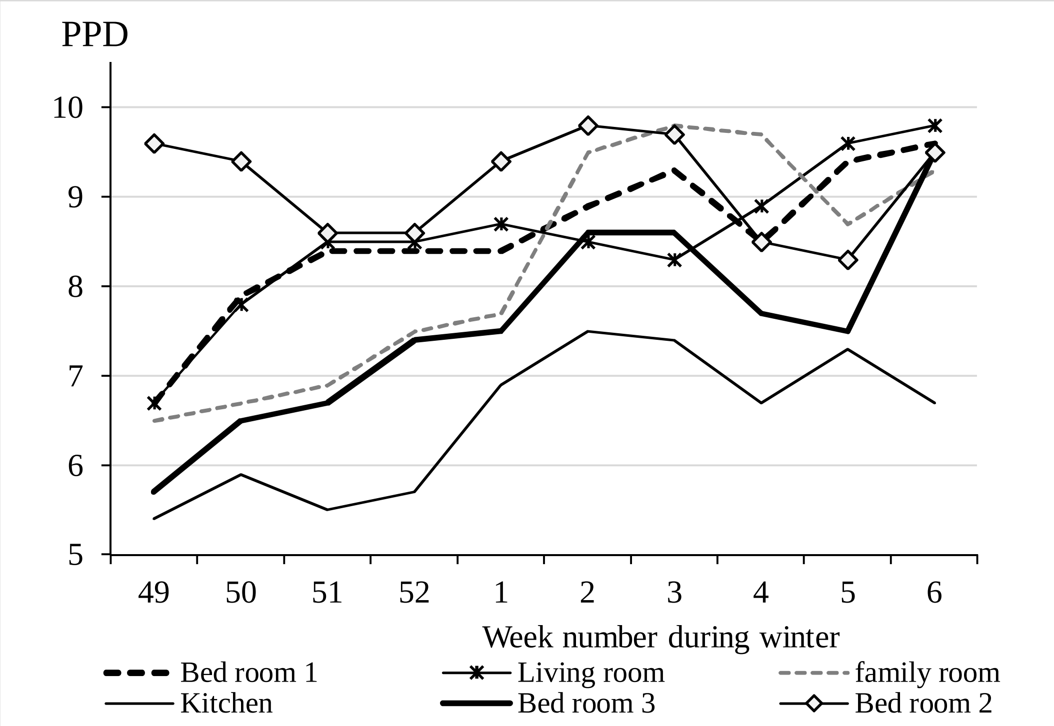

Figure: 5.23: PPD for all the corresponding zones in case study building 1 during winter

The X-axis showing the week number started from the second week of december and continues until the second week of February. The Y- axis is showing the PPD range. It can be seen that the week number plotted in the X-axis showing the typical winter week from December till February. The overall PPD index in all of zones showing a satisfactory level. The PPD is equally distributed as can be seen and the range is between 5 and 9.5. The living room is showing a similar situation where the trend line reaches slightly higher than 9. The scenario in Bedroom 2 is different. The trend line for bedroom 2 is relatively close to the threshold limit of 10 % compared to other zones. The PPD level variations at a certain point reaches the peak of 9.8 as can be from the figure. From figure 5.9 it was proved that the operative temperature in the kitchen, especially after renovation, increases during the evening hours due to internal gains from occupants and equipments. But it did not negatively influence the PPD index (see figure 5.23). According to the table 4.7 mentioned in the methodology section, the renovated building falls within category II which is under the rating of Miljöbyggnad gold.

Figure 5.24 shows the simulation result for all the zones during summer in case study building 1. It shows the PPD index after the successful implementation of the shading devices in the renovated case study building 1.The week number plotted in the X-axis showing the week started from the third week of June utill the third week of August. On the contrary, the Y-axis is showing the PPD range.

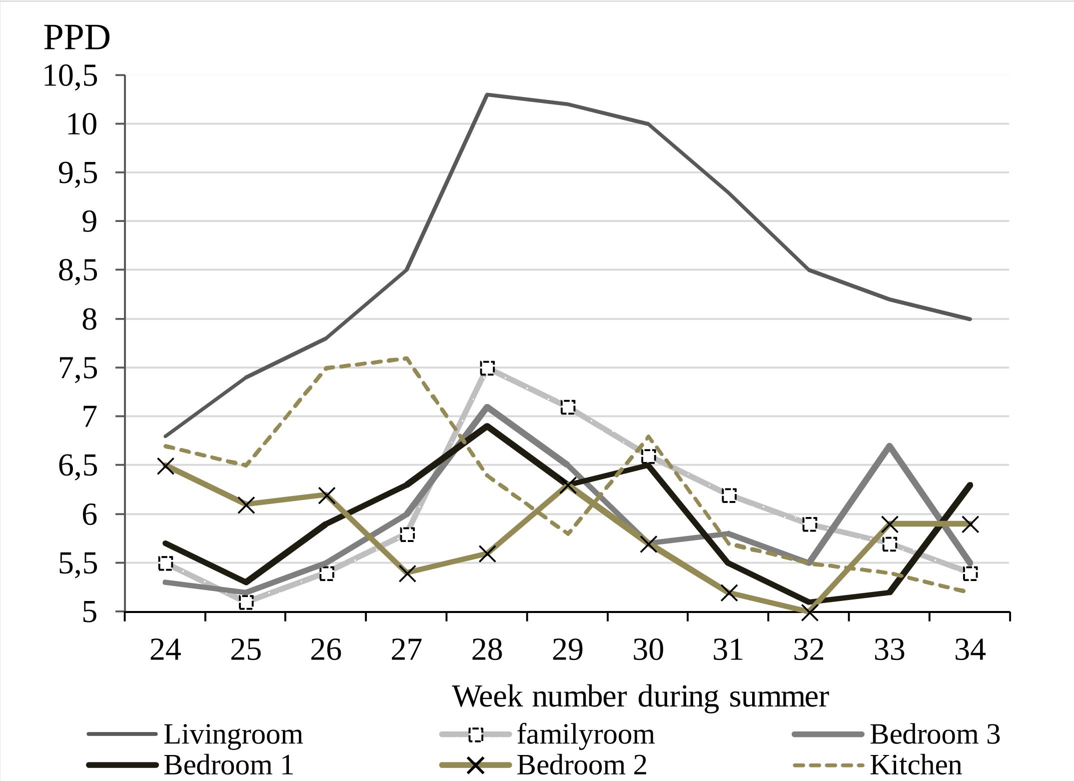

Figure: 5.24: PPD for all the corresponding zones in case study building 1 during summer with external shading

Looking at the individual zones, the trend did not seem to cross the threshold limit of 10% in all the zones except living room. During 28th week in summer the PPD is more than 10 in the livingroom Although the bedroom 3 is situated towards the southwest as living room, the scenario for the indoor thermal environment was comparatively better in bedroom 3. Because the shading device efficiently minimized the overheating hours in Bedroom 3. The PPD level kept the ideal condition and reached up to the level of 9.5 but seem to have a sudden drop afterwards and stabilized at around 6.5%. The individual trend for two other bedrooms successfully kept the PPD range within the standard. The family room had the advantages, and it can be seen that the trend seem to increase but soon after had a sharp decrease until reaches at the minimum threshold of 5%.

Figure 5.25 and 5.26 showing the PPD analysis for all zones during winter in the renovated case study building 2. The simulations were performed for the typical winter weeks. Therefore, weeks plotted in the X-axis showing the week number started from December and continues until the second week of February.

All of the bedrooms showing the similar PPD level variations except for Bedroom 4. The PPD in the bedroom showing a sharp increase in the first few weeks during winter and then afterwards during the first week of February i.e in the 5th week a sharp decrease is noticeable. It is observed that Bedroom 1and Bedroom 2 kept the trend line close to each other.

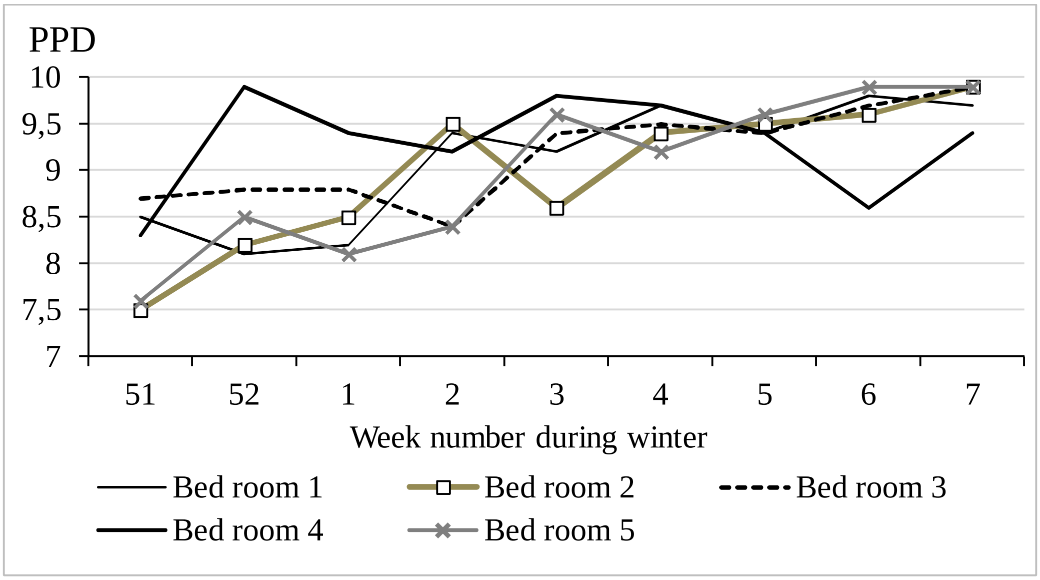

Figure: 5.25: PPD for all bedrooms in renovated case study building 2 during winter

The minimum PPD level obtained in Bedroom 1 and Bedroom 2 was 7.5 and 8.1 which reached the peak of 9.7% and 9.8% respectively. It can be seen that all of the Bedrooms does not have wide variations towards the PPD level, and the corresponding PPD range was 7 - 9. Figure 5.26 shows that living room and family room had similar variations in the PPD level until January i.e 3rd week in the graph and changed afterwards in the following months.

The trend showing a continuous increase or decrease until it reaches the PPD of around 9.8 in the family room and 9.6 in the living room (see figure: 5.26). The maximum PPD level in the kitchen can rise up till 9.5 in case study building 2 while on the other hand for case study building 1 the upper limit can go up till 7.5%.

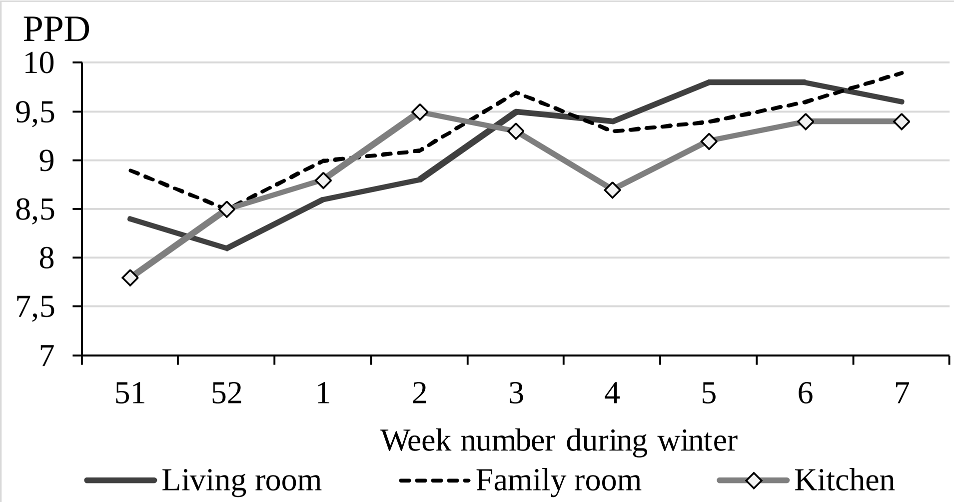

Figure: 5.26: PPD for living room, family room, and kitchen during winter

Figure 5.27 showing the PPD condition during summer in case study building 2. The week number plotted in the X-axis showing the week started from the third week of June utill the third week of August. While on the other hand, the Y-axis is showing the PPD range. The trend for bedrooms located in the northwest showing similar variations in the PPD level except for bedroom 5 which is situated towards the southeast. Bedroom 3 and bedroom 4 reaches the peak of 9% during the summer week of 31^{st} (Figure: 5.27). The bedroom 1 and bedroom 2 situated on the ground level has comparatively less variations in the PPD level and the range is between 5 and 7. It shows a reduction in the maximum PPD level by 2 and 2.3 in Bedroom 1 and bedroom 2 respectively compared to bedroom 3 situated at the first floor level.

The figure presented below show the thermal comfort condition for all of the corresponding zones during summer. Figure 5.27 shows that the trend for family room reaches the peak of 10.5 % although the shading has been considered while simulating. It seems that the family room has the worst condition in terms of PPD. The external Venetian blind could not minimize the temperature indoor that can be seen from figure 5.18 which generates higher PPD level in the family room. It is worth mentioning that the simulation period considered was third week of June till third week of August.

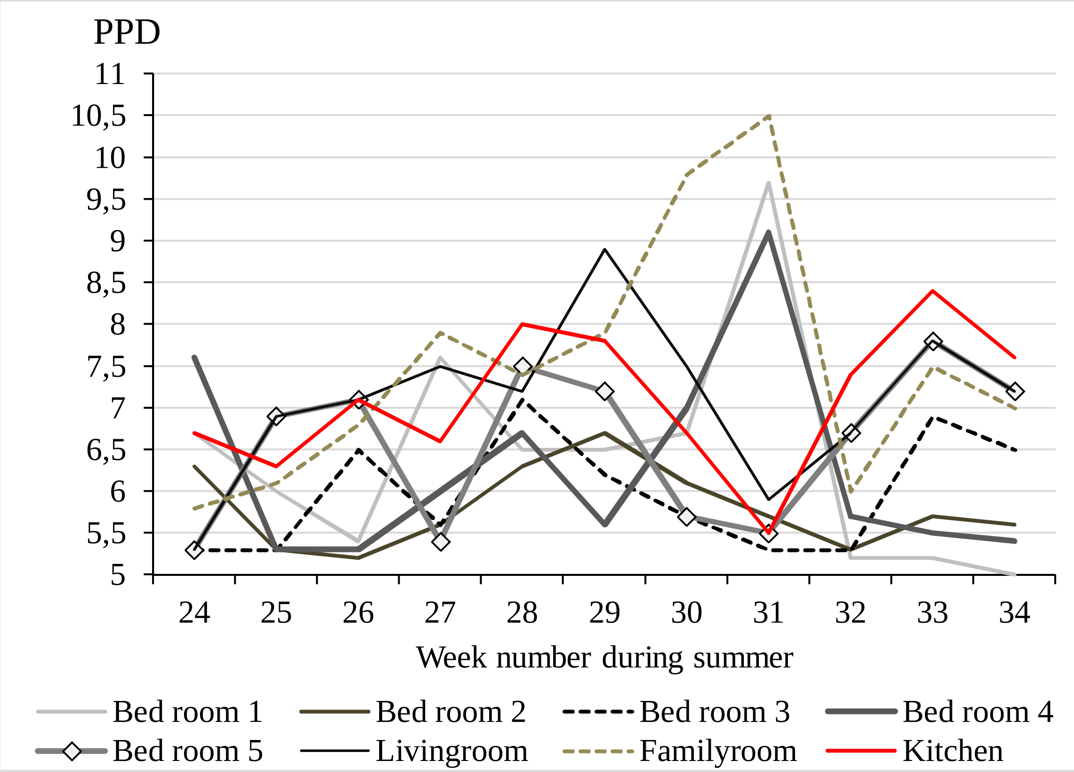

Figure: 5.27: PPD for all the corresponding zones in case study building 2 during summer with external shading

The PPD level is low at the beginning of summer weeks which started to increase substantially and the maximum peak can be seen as 10.5%. Although the living room and family room both situated towards the southwest but on two different levels. The living room did not cross the threshold limit of 10%. It means that the thermal environment is acceptable. The kitchen had moderate fluctuations in the PPD level, and the range is 6 to 8. Therefore, except the family room the other two zones living room and the kitchen was proved as comfortable throughout the summer weeks. Both of the rooms attained the gold rating in Miljöbyggnad.

6 Discussion

This section will present an in-depth analysis of the objectives derived in section 1.2. Simulations were performed to investigate the questions addressed in the objectives. It is worth mentioning that the individual energy-efficient strategies were not simulated for performing the thermal comfort analysis, but all the measures were incorporated simultaneously to assess the thermal comfort condition. The most influential parameter was Mechanical ventilation system with heat recovery efficiency of 80%. It not only reduced the energy use considerably but the thermal comfort level was satisfactory when mechanical ventilation system was introduced in the renovated building. The renovation measures elevated the indoor thermal environment and enhanced the comfort level of the occupants compared to the existing building. Based on the literature review the environmental impact can be minimized through energy-efficient strategies that contributed to the potential energy saving. It can ensure satisfactory thermal comfort in the renovated buildings which has been proved in the earlier result section. The discussion will further explore the relationship between energy efficient strategies and thermal comfort. The parameters were strictly followed by the Swedish standard such as FEBY and Miljöbyggnad. So, the results will be evaluated accordingly. It should be mentioned that the solutions were aimed for single-family residences and hence might not be the accurate solutions for the multifamily residential buildings. Since all of the measurements were set in accordance with the criteria for a single-family residence. This section will discuss the following topics:

- The impact of FEBY model and Stochastic approach on the final energy use
- Relationship between energy efficient strategies and thermal comfort
- The influence of shading device in thermal comfort

6.1 The impact of FEBY model and stochastic approach on energy use

It was difficult to schedule the behavior pattern of the occupants. So, a detailed schedule for behavior pattern and energy use of the occupants was developed by the author based on the assumptions for four occupants (two adults and two children). The stochastic model developed by Widen and Wäckelgår *(Widén & Wäckelgår, 2010)* was followed to make a detailed schedule for occupant behavior. It is not possible to make assumptions regarding every activity of human behavior. Therefore a feasible prediction was made. The age factor was also important to shape an outline for the stochastic approach. Occupant's presence and absence in each of the zone influenced the final energy use. FEBY 12 takes into consideration the average household electricity based on the seasonal changes, but it does not consider the behavior pattern of the occupants. One of the most important parameters in stochastic approach was the diurnal changes based on the zone activities. However, for individual energy efficient strategies stochastic approach did not contribute to a reduction in energy use compared to the FEBY schedule. The detailed schedule may overheat the house at times and other times the house can be solely heated by the heating system without any contribution from the internal gains. While on the contrary FEBY model always takes into consideration internal gains for heating the house. According to Sveby, the household electricity is 30 kWh/m² and 70% of this can be calculated as useful for heating.The stochastic model was precisely scheduled in comparison with FEBY 12. Moreover, the result indicates that a more detailed schedule can increase the energy use to a great extent. The final energy use in case study building 1 and 2 according to the stochastic model is 6 kWh/m² and 4.2 kWh/m² more than the standard FEBY model. Although the energy use increases, it stays within the limit of FEBY standard.

The existing activity pattern was developed from Markov chain model which represents the variations in lighting and equipment use. The trend of activity patterns for lighting and occupancy (see figure 4.5 and 4.6) showed realistic fluctuations depending on the seasonal, weekdays and weekend variations. However, changes in the behavioral pattern can change the probability for presence or absence in different zones which can highly influence the final energy use of a building. In this thesis with the help of a scientific model a detailed profile for occupant behavior was designed. Instead of an average value, this scientific approach can be applied to design a user profile for occupant behavior. It was really helpful to get a precise overview regarding the energy use. Previous research does not explicitly show the relationship between a standard model and stochastic approach. In this thesis it was shown that the energy use can differ to a great extent between a Feby model and a detailed schedule for occupancy, lighting and equipment.

6.2 Relationship between energy-efficient strategies and thermal comfort

Energy-efficient renovation and thermal comfort are correlated to each other. It should be emphasized that the standard FEBY 12 was taken into consideration for energy use, and Miljöbyggnad was set as a reference for thermal comfort. While simulating the thermal comfort in IDA ICE the energy simulation acts as a fundamental part of the process.

This section will discuss the relationship between energy use and thermal comfort based on the results obtained through the simulations.The thermal comfort condition before and after renovation was investigated for both of the case study buildings. The renovation measures were one of the fundamental objectives. It is going to be discussed from the simulation perspective. Thermal comfort is a complex mechanism and is different according to climate, types of residential and commercial settings, etc. The satisfaction level from physiological and psychological perspective is different for each of the persons. Hence to ensure an optimum level of temperature in each of the zones is undoubtedly difficult. Different parameters such as mean air temperature, operative temperature, activity and clothing level were evaluated for two case study buildings. The implications of these parameters can vary to a great extent.

The simulation result showed before renovation very high energy use (see figure 5.1 and 5.2) for both of the case study buildings. The poorly insulated building envelope and the lack of heat recovery contributed to larger heat losses. The possibility of linking the energy efficient strategies and thermal comfort was the driving force for further investigation. As a residential building, there exist some recommendations which have been followed accordingly. The result showed that building envelope has a profound influence on the PPD level. The corresponding PPD was higher than 25%, and PMV was showing very high cold sensation during the heating season. The percentage of dissatisfaction among the occupants are irrespective of all zones. It can be interpreted that a poorly designed building envelope cannot ensure minimum comfort level to the occupants situated in a cold climate although the condition showed a reasonable PPD level during the warmer months (Figure: 5.20) . However, the result for bedroom 1 showed the PPD index below 10% during summer in the existing building which is not true in reality. Because it is not possible to maintain a comfortable indoor environment throughout the summer period without any shading installed or window airing. Considering the impact of all the energy efficiency strategies the reduction in energy use compared to the existing building resulted in 71% and 69% in the case study building 1 and 2. Mechanical ventilation with heat recovery was proved as one of the most energy-efficient strategies. It minimized the heat loss drastically and reduced the energy usage successfully up to the FEBY standard level. Further analysis on thermal comfort showed that during the heating season indoor thermal environment in the upgraded building envelope is remarkably good and keep the temperature within the comfort range.

After analyzing the PPD index for all the corresponding zones before and after renovation in both of the case study buildings, some significant factors have been identified. The reduction in solar gains was one of the most influential factors which highly influenced the comfort level. The scenario is true especially for the zones situated towards the southwest. On the contrary, the zones situated towards south were comparatively warm during winter resulted in better thermal comfort state. It is worth mentioning that in case study building 1, the internal gains from equipment, lighting, and occupants successfully contributed to increasing the temperature at a certain level. It helped to maintain the desired PPD level. Before renovation the living room in case study building 1 retained the maximum PPD level 26% during the heating season. The renovated building contributed to 74% reduction in PPD level during the heating season. The existing building could not make it under the rating for Miljöbyggnad “Bronze”, but the renovated building successfully achieved the requirement for Miljöbyggnad ‘Gold’. The bedroom 5 in the case study building 2 had the highest PPD with approximately 24.5%. The PPD level in the renovated building was reduced by 69% compared to the existing building. The renovated building obtained the desired rating for Mijöbyggnad ‘Gold’ since the corresponding PPD level was below 10% during the heating season. It was signified that both of the case study buildings showed improvements regarding the PPD level during winter. Now, the following section will discuss the effect of shading installation in the indoor thermal environment during summer.

6.3 The influence of shading devices in thermal comfort

The possibility for improving the building condition by any specific measures can also bring about an unfavorable impact to the indoor environment. It is necessary to keep a certain balance that could minimize the probability for any negative impact in the building. Based on the analysis for overheating hours, it was taken into consideration to implement shading. Depending on the overheating hours different types of shading with specific glazing types were evaluated to minimize the excessive solar gains. The shading device was installed for typical summer weeks considering the higher temperature outdoor. It is difficult to ensure a satisfactory level of thermal comfort and the admission of adequate daylight simultaneously. There are certain factors to consider for solar gains such as the time period of exposure to sunlight, the solar angle, etc. Each zone in the building cannot receive the same amount of solar gains so it will differ accordingly. The living room was functionally the most active zones, so analyzing the thermal comfort in different seasons was very useful. The external shading device efficiently minimized the solar gains penetrating inside and resulted in less radiative heating inside.

The Livingroom and Bedroom 3 in case study building 1 obtained the maximum PPD of 16% and 18% respectively during August. The implementation of shading reduced the PPD level during August considerably by 48% and 67% compared to the existing building. But as a matter of fact during July, the PPD level exceeded the 10% range and could not achieve the ‘Gold’ rating. The scenario for PPD showing the highest value for Livingroom and Family room with 13.5% and 12% during July in the existing building. It was decreased by 27% and 37.5% in the family room and living room simultaneously after the addition of shading. The values obtained the gold rating in Miljöbyggnad. It is important to be noted that during June the PPD level exceeded the threshold of 10 % in the family room despite the fact that shading device was on. A few contributing factors such as orientation and window to wall ratio (WWR) can influence the PPD level highly. The window to wall ratio (WWR) was investigated because the energy consumption can be affected by this factor. The glazing area in southwest and southeast facade was around 56% and 10% of the total facade area in case study building 1. The WWR (window to wall ratio) was maximum in the southwest facade. The maximum glazing area can be beneficial for the solar gains during winter. But the simulated result showed that the zone suffered excessively from overheating periods. It resulted in an uncomfortable indoor environment for the occupants. Moreover, it was observed from the overall state that except the Livingroom in case study building 1 and family room in case study building 2 the PPD level in all of the zones during each of the summer months falls within the gold rating of Miljöbyggnad.

7 Conclusions

The performance of two Swedish single-family residential buildings was evaluated in terms of energy use and thermal comfort before and after an extensive energy renovation. Different heating system, energy use for heating and DHW, building regulations etc. have provided the background necessary for further analysis of the single-family residences. The interdependence between the energy efficient renovation and thermal comfort was found interesting. The purpose was aimed at two specific goals. Reducing the potential risk of global warming by adopting energy-efficient strategies and how the energy efficient strategies could improve the thermal comfort level of the occupants. The paper gives a clear idea and a good representation of applying the Swedish standard FEBY and Miljöbyggnad. All the energy efficient renovation strategies and each of the steps for the energy calculation was followed strictly by the Swedish standard FEBY. The comfort demand of the occupants in recent decades have ameliorated in an enormous pace due to the technological advancement. It has a major contribution in the total energy consumption. The thesis explores the energy use in two different scenarios such as FEBY model and stochastic approach. The result showed that it is possible to decrease the energy usage up to 71% if the FEBY standard is applied.

Building simulation is an essential process for optimizing the energy performance. The uncertainty of different parameters need to be assessed from a logical perspective. The stochastic nature of input data should be taken into account and uncertainty analysis should be performed. The FEBY model does not take into consideration the stochastic nature of the input parameters so the simulated energy use of the building can be different from the real energy use. There is a probability for the discrepancy between the assumed and actual infiltration rate which can influence the energy use of a building. Although the renovation strategies were performed according to the passive house standards it is a matter of fact that the impact of climate change was not considered on this occasion. So, the building may not withstand the future climate change impact. The assumptions for occupant behavior, lighting, and equipment use can negatively influence the energy use. Therefore, it is important to design the mentioned parameters accurately because the careful consideration for the reasonable inputs can lead to optimum outputs.

The low energy use and comfortable indoor environment are two important aspects of any studied building. This paper emphasized on the thermal comfort level before and after renovation. The simulation result for operative temperature and PPD analysis showed improved thermal environment indoor in the renovated building compared to the existing building. The renovation has major impact on the thermal comfort level of the occupants. From the analysis and simulation result, it can be concluded that the renovated case study buildings maintained an optimum operative temperature indoor. Consideration for orientation is also necessary while designing the layout of the building. Large windows towards southwest should be avoided since the risk for overheating increases during summer. To avoid higher operative temperature indoor during summer, the use of external shading device was beneficial. The energy-efficient appliances helped to maintain the indoor temperature successfully within the comfort range during winter. In the existing building when the minimum level Bronze from Miljöbyggnad was not achieved it clearly identified that the building was poorly optimized. The renovated building attained the gold rating which indicates that the occupants will feel comfortable in any given condition. Moreover, this study can serve as a guideline for obtaining a comfortable indoor thermal environment in renovated single-family residential buildings.

7.1 Future work

It was mentioned in the limitation section that no qualitative methods were taken into consideration. It means that the the residents living in the single-family residences were not interviewed neither the perceived thermal comfort condition was assessed through questionnaire. Therefore, in the future work post occupancy evaluation through interviewing the residents or questionnaire survey can be performed to assess the indoor thermal condition in the single-family residences. A comparative analysis can be performed between the simulation result and the results obtained from the occupants. Similar methods of thermal comfort can be applied for Multifamily apartments to identify the thermal comfort level of the occupants.

8 Summary

The worldwide energy consumption is growing rapidly due to the technological advancement, infrastructure and population growth. As a result, the CO_2 emission is also increasing everyday. In Europe, the building sector is responsible for around 40% of the total energy use that give rise to 36% of the European Union's total CO_2 emission.

A total of one million single-family and multifamily residential houses were built in Sweden during 1965 and 1975 to minimize huge housing shortage. It was an initiative by the Swedish government and the inititative was named "The Million Program". There are 1.9 million single-family houses in Sweden which currently represent 30% of the total residential building stock. The residential houses built during the Million Program are more than forty years old and majority of them need renovation. As a consequence, the opportunities for implementing the energy efficiency measures became prevalent. Existing studies show that houses situated in cold climates can gain benefits by adopting energy-efficient renovation. However, thermal comfort of the occupants is often ignored as the prime focus of renovation is to reduce the energy consumption. Several study reports show that the thermal comfort level in the buildings from the Million Program is not satisfactory. Therefore, this study addresses the key issues of energy-efficient renovation and thermal comfort.

Due to individual or private ownership and cost issues, the rate of renovation in single-family residences is comparitively lower than multi-family residences. Hence, there exists limited research on renovation for single-family residences in comparison with multi-family residences. The purpose of this study is to establish the influence of energy-efficient renovation on energy use and thermal comfort in two Swedish single-family residences built during the Million program. The changes in the thermal comfort of the occupants before and after adopting the energy-efficient strategies was investigated thoroughly. This paper adds value to the energy-efficient renovation and thermal comfort study through appropriate analysis and design considerations. However, it is important to mention that this study is solely based on the simulation results and analysis through scientific methods. Therefore, no physical measurements have been carried out throughout the study.

The methodology is based on the actions performed during the study. A quantitative method was applied to identify the driving factors for improving the thermal comfort of the occupants through efficient energy use. Renovation strategies followed by the simulations were performed from two different perspectives namely the Feby model and Stochastic approach. The goal was to evaluate the impact of these approaches on energy use. The energy-efficient renovation was considered as a key driver for the thermal comfort studies. The assessment of thermal comfort condition before and after renovation played a significant role to distinguish between two different scenerios. The thermal comfort analyses were performed based on the current scientific methods. From simulation the operative temperature, overheating hours and PPD (predicted percentage of dissatisfied) were found as three important

parameters that helped to determine the indoor thermal condition. Finally, a comparative analysis were performed between the simulated results and the scientific equations accompanied by different international standards to evaluate the thermal comfort condition indoor.

Scientifically, the stochastic model presented in this thesis exhibits a precise overview regarding the energy use in comparison with the standard Feby model. The stochastic model can be developed further to design specific occupant behavior as it highly influences the energy use in single-family residences. This study sheds light on the energy use pattern between a standard model and a stochastic approach.

The correlation between energy-efficient renovation and thermal comfort showed the possibility to identify an optimum result. The energy-efficient strategies were found beneficial in terms of energy use and enhanced the thermal comfort level of the occupants in the case study buildings. The building envelope has profound influence on the PPD level.The simulated result showed higher rate of dissatisfaction among the occupants in non-renovated case study buildings. On the contrary, the predicted percentage of dissastisfaction (PPD) was below the threshold limit in renovated case study buildings. The Swedish standard Miljöbyggnad was set up as a standard to compare the level of thermal comfort achived in different scenerios. The well-insulated and airtight building envelope secured 'Gold' rating during winter under Miljöbyggnad. It implies that the thermal comfort level is well maintained in two case study buildings. The addition of shading showed reduction in overheating hours and retained the operative temperature in a comfort range. Apart from that, higher window-to-wall ratio was noticed in the southwest oriented rooms which resulted in higher operative temperature indoor especially during summer. Therefore, this study emphasizes on careful considerations on window-to-wall ratio and the orientation to avoid uncomfortable environment indoor.

The knowledge presented in this study can be fruitful for further exploration of thermal comfort in the single-family residences from the Million program. Results obtained through different phases of the study can provide guidelines to enrich the indoor thermal comfort.

9 References

Adamson, B. (2011). *Towards Passive houses in cold climates as in Sweden.* Lund University.

ASHRAE standard. (2013). *Thermal Environmental Conditions for Human Occupancy.* ANSI/ASHRAE Standard 55-2013.

Atanasiu, B., Despret, C., Economidou, M., Maio, J., Ingeborg, N., & Raph, O. (2011). *Europe's buildings under the microscope-a country by country review on the energy performance of the buildings.* BPIE (Building performance institute Europe).

Björk , C., Nordling, L., & Reppen, L. (2011). *Så byggdes villan : svensk villaarkitektur från 1890 till 2010* (2nd ed.). Svensk Byggtjänst.

Björk, C., Hordling, L., & Reppen, L. (2011). *Så byggdes Villan, Svensk villa arkitektur från 1890 till 2010.* Svensk Byggtjänst.

Bornehag, C. G. (2014). Miljöexponeringar tidigt i livet,epigenetiska förändringar och risken för sjukdomar senare i livet. In C. Jernbro, C. G. Bornehag, & S. Janson (Eds.), *Barns liv och hälsa i Varmland 2014* (pp. 178-180). Karlstad.

Boverket. (2009). *Enkätundersökning om boendes* . Karlskrona: Boverket Publicationsservice.

Boverket. (2009). *Så mår våra hus - redovisning av regeringsuppdrag beträffande.* Karlskrona: Boverket.

Brager, R., Dear , R. d., & Cooper, D. (1997). *Developing an adaptive model of thermal comfort and preference.* Australia.

Building performance institute in Europe(BPIE). (2015). Europe´s Buildings under the microscope. A country by country review of the energy performance of buildings.

Dujardin, F., Marique , A., & Teller, J. (2014). Spatial planning as a driver of change in mobility and residential energy consumption. *Energy and buildings, 68,* 779-785.

Elmroth , A., & Abel, E. (2007). *Buildings and Energy - A Systematic approach.* Stockholm: Forskningsrådet Formas.

Energymyndighet. (2014). *Energy statistisk for små hus.* Statens energymyndighet.

Eurostat. (2016). *Joint research commission*. Retrieved from Eurostat Statistics: http://ec.europa.eu/eurostat/statistics-explained/index.php/Statistical_themes

Eurostat staistics, JRC. (2016). *Joint research commission*. Retrieved from http://ec.europa.eu/eurostat/statistics-explained/index.php/Statistical_themes

Fanger, P. O. (1970). Analysis and applications oin Environmental engineering. In *Thermal comfort.* Copenhagen: Copenhagen: s.n.

FEBY. (2012). *Forum for energy efficient buildings*. Retrieved 2016, from http://www.nollhus.se/

Fennel, H., & Haehnel, J. (2005). Setting airtightness standard. *Ashrae journal, 47*, 28-29.

Gagge, A., & Nevins, R. G. (1976). *Effect of energy conservation guidelines on comfort,acceptability and health.* Federal Energy Administration, New Haven pierce lab.

Ghashemi, M. (2015). *Behavior related energy use in Sweden, A study in residential houses in Sweden.* Stockholm: KTH Royal institute of Technology.

Givoni, B., & Goldman, R. (1973). Predicting effects of heat acclimatization on. *Applied Physiology, 35,* 875-879.

Government offices of Sweden. (2008). *Government offices of Sweden*. Retrieved 2015, from http://www.government.se/

Hellström, A., & Sandkvist, O. (2010). *Energibesparing inom miljonprogrammet– är miljömålen 2020 och 2050 rimliga?* Lund: Lund University .

Henning, A. (2010). Vem fattar beslut om värmesystemen i monteringsfärdiga småhus? In *Klimatsmart villavärme? Solvärme, nya byggregler och möjligheten att förändra* (pp. 15-25). Falun.

Humhreys, M. (1979). The influence of season and anbient temperature on human clothing behaviour. In P. Fanger, & O. Valbjörn (Eds.), *Indoor climate.* Copenhagen: Danish building reserach.

International Energy Agency. (2008). *Energy technology perspective.*

International Energy Agency. (2014). *Methodology for Cost-effective Energy and Carbon emission optimization in building renovation.* Portugal: University of Minho.

Ioannou, A., & Itard, L. C. (2015). Energy performance and comfort in residential buildings: Sensitivity for building parameters and occupancy. *Energy and buildings, 92*, 216-233.

IPCC. (2007). *Climate change ,2007 Impacts , Adaptation and Vulnerability.* London: IPCC.

ISO. (1984). *Moderate thermal environments - determination of the PMV and PPD indices and specification of the conditions for thermal comfort.* International Standard ISO 7730.

Johansson, D., Bagge, H., & Lindstrii, L. (2011). Measured occupancy levels in 18 Swedish Apartment buildings-application to input data for building simulation. Sydney: International builidng performance simulation association.

JRC. (2013). *Trends in global CO2 emission.* Hague, Netharlands: Joint Research Centre (JRC).

Kildsgård, I., & Prejer, E. (2011). *Främtidens trähus-energieffektiva med god innemiljö.* Stockholm: Swedish environmental research institute.

Mahapatra, K., & Gustavsson, L. (2013). Energy renovation of single family houses: importance of economic aspects and suggested policy measures. *ECEEE*. France.

Mahapatra, K., Gustavvson, L., & Nair, G. (2010). Energy renovation of single-family houses: importance of economic aspects and suggested policy measures. *Energy Policy, 38*(6), 2956–2963.

Meggers, F., Leibundgut, H., Kennedy, S., Qin, M., Schalaich, M., Sobek, W., & Sukuya, M. (2007). Reduce CO2 from buildings with technology to zero emission conservation of historic buildings. *Sustainable cities and society, 21*, 29-36.

Nicol, F., & Stevenson, F. (2013). Adaptive comfort in an unpredictive world. *Building research and information, 41*, 255-258.

Nicol, F., Jake, H., Brian, S., & Davis, H. (2008). Suggestion for new approach to overheating diagnostics. Windsor.

Nilsson, P. E. (2003). *Achieving the desired indoor climate: Energy efficiency aspects of system design.* Lund: studentliterature AB, Sweden.

Peeters, L., Dear, R. d., Hensen, J., & Haeseleer, W. D. (2008). Thermal comfort in residential buildings: Comfort values and scales. *Applied energy, 86*, 772-780.

Perman, K. (2011). Swedish building policy and the manufacturers of single family houses in the county of Dalarna.A collaboration of the future goal of the improvement of energy efficiency? Linköping: World renewable energy congress.

Power, A. (2008). Does demolition or refurbishment of old and inefficient homes help to increase our environmental, social and economic viability? *Energy Policy, 36*(12), 4487–4501.

Preiser, W., & Vischer, J. (2006). *Asessing building performance.* london: Elsevier.

REHVA federation of European heating, v. a.-c. (2012). *Indoor environmental input parameters for design and assessment of energy performance of buildings- addressing indoor air quality, thermal environment, lighting and acoustic.*

Rohdin, P., Molin, A., & Moshfegh, B. (2014). Experience from nine passive houses in Sweden -Indoor thermal environment and energy use. *Building environment, 71*, 176-185.

Santin, O., Itard, L., & Visscher, H. (2009). Ther effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock. *Energy and buildings, 41*(11), 1223-1232.

Shafqat, O. (2011). *Decreasing energy use by 50% in Swedish multifamily residential buildings by 2050, obstacles and opportunities.* Stockholm: Department of Energy Technology.

Singh, M. (2010). Thermal monitoring and Indoor temperature Modeling in Vernacular buildings of North-East India. *Energy and buildings, 42*, 1610-1618.

Singh, M. K., Mahapatra, S., & Baruah, P. (2014). Thermal comfort in naturally ventilated classrooms. Ahmedabad: International conference PLEA.

Singh, M. K., Mahapatra, S., & Teller, J. (2014). Relation between indoor thermal environment and renovation in Liege residential buildings. *Thermal science, 18*, 889-902.

Singh, M. K., Mahapatra, S., & Teller, J. (2014). Relation between indoor thermal environment and renovation in Liege residential buildings. *Thermal science, 18*, 889-902.

Singh, M., Mahapatra, S., Atreya, S., & Givoni, B. (2010). Thermal monitoring and Indoor temperature Modeling in Vernacular buildings of North-East India. *Energy and buildings, 42*, 1610-1618.

Statistika. (2015). *Staistiska Centralbyrån*. Retrieved 2015, from http://www.scb.se/en_/Finding-statistics/

Stephen, S., Coley, D., & Wilde, P. D. (2011). Comparing the robustness of building regulation and low energy design philosophies. Conference of international building performance simulation association.

Sunikka, M. (2006). Policies for improving Energy efficiency in the European Housing stock. In *Policies for improving Energy efficiency in the European Housing stock.* IOS press.

Swedish energy Agency. (2013). *Energymyndigheten*. Retrieved 2015, from http://www.energimyndigheten.se/

Svenska Kyl och Värmepump föreningen. (2014). *Svenska Kyl och Värmepump föreningen*. Retrieved 2015, from http://skvp.se/varmepumpar/villa

Thollander, P., Rohdin, P., Moshfegh, B., Karlsson, M., Söderström, M., & Trygg, L. (2013). Energy in Swedish industry 2020-current status,policy instruments and policy implications. *Elsevier, 51*, 109-117.

Thomas, H., & Viden, S. (2005). The Million Homes Programme: a review of the great Swedish planning project. *Planning Perspectives, 20*, 301-328.

Thomson, A., & Filer, V. d. (2009). Replacement or renovation of dwellings : the relevance of a more sustainable approach. *Building research and information, 37*, 649-659.

Tommerup, H., & Svendsen, S. (2005). Energy saving in Danish residential building stock. *Energy & Buildings, 38*(July,2005), 618-626.

UNEP. (2009). *Buildings and climate change.* Paris: UNEP SBCI sustainable buildings & Climate initiative.

Vanhoutteghem, L., Tommerup, H., Svendsen, S., Paiho, S., Juusela, M., Mahapatra, K., Aabrekk, E. S. (2012). Full-service concept for energy-efficient renovation of single family houses. Denmark.

Warfvinge, C. (2008). *Mycket energi att spara i miljönprogrammet* . VVS forum .
WBCSD. (2007). *World Building council for sustainable development.*

Vedung, E. (2001). *The politics of Swedish energy policies. In buildings sustainable energy systems.* Siveira, Svenska Byggtjänst and Swedish national energy administration.

'

Viden , S., & Lundhal , G. (1992). *Miljonprogrammets bostäder : bevara - förnya - förbättra.* Formas.

Widen, J., & Wäckelgård, E. (2010). A high resolution stochastic model of domestic activity patterns and electricity demand. *Applied energy, 87*(6), 1880-1892.

Yohanis, Y., Mondol, J., Wright, A., & Norton, B. (2008). Real life energy use in the UK : how occupancy and dwelling characteristics affect domestic electricity. *Energy and Buildings, 40*, 1053-1059.

Appendices

A.

The author greatfully acknowledges permission to use materials from the following sources. The source and the names of the authors are listed below:

No.	Source	Name	Authors	Figure number & page no.
1.	Conference proceedings	Energy renovation of single-family houses: the importance of economic aspects and suggested policy measures	Krushna Mahapatra & Leif Gustavsson	Fig 1.1, Page 7
2.	Book	Så byggdes Villan: Svensk Villaarkitektur från 1890 till 2010	Cecelia Björk. Lars Nordling & Laila Reppen	Fig 2.8 Page: 23
3.	Book	Så byggdes Villan: Svensk Villaarkitektur från 1890 till 2010	Cecelia Björk. Lars Nordling & Laila Reppen	Fig 2.9 Page 24
4.	Book	Så byggdes Villan: Svensk Villaarkitektur från 1890 till 2010	Cecelia Björk. Lars Nordling & Laila Reppen	Fig 2.10 Page 24
5	Journal article	A high-resolution stochastic model of domestic activity patterns and electricity demand	Joakim Widen & Ewa Wacklegård	Fig 4.3 Page 34
6.	Journal article	A high-resolution stochastic model of domestic activity patterns and electricity demand	Joakim Widen & Ewa Wacklegård	Fig 4.4 Page 34
7	Book	Så byggdes Villan: Svensk Villaarkitektur från 1890 till 2010	Cecelia Björk. Lars Nordling & Laila Reppen	Figures on the cover page

B.

Table: 1 : Thermal Bridge calculation for case study building 1

	U/ (W/(m²·K))	A / (m²)	UA/ (W/K)	$UA_{effective}$/ (W/K)
Windows	2.90	24.75	71.77	
Doors	1.50	18.30	27.45	
Walls	0.44	181.25	79.75	
Roof	0.26	109.81	28.55	
Ground	0.17	113.62	19.31	
Total (Average U value)	1.05	447.73	226.83	209.6

25% of the building envelope is considered as thermal bridges.

Therefore, $0.25 \times \frac{UA}{A}$

$$= 0.25 \times \frac{226.83}{447.73}$$

$$= 0.12$$

Table 2: Thermal Bridge calculation for case study building 2

	U/ (W/(m²·K))	A / (m²)	UA/ (W/K)	$UA_{effective}$/ (W/K)
Windows	2.60	17.18	43.70	
Doors	1.50	3.35	5.02	
Walls	0.27	128.48	34.78	
Roof	0.18	82	14.76	
Ground	0.17	81	13.77	
Total(Average U value)	1.11	312.01	112.03	111

25% of the building envelope is considered as thermal bridges.

Therefore, $0.25 \times \frac{UA}{A}$

$$= 0.25 \times \frac{112.03}{312.01}$$

$$= 0.09$$

C.

Table: 3 : Solar gains for different window U values

	Solar gains/kWh				
	g-value				
	0,7	0,68	0,61	0,55	0,5
	U-value / (W/(m²·K))				
	2,9	1,9	1,4	1	0,8
January	139	135	121	109	101
February	339	329	295	266	247
March	695	675	606	546	507
April	924	898	807	729	676
May	1326	1278	1168	1071	1005
June	953	898	834	778	741
July	510	468	438	413	397
August	756	707	657	613	585
September	715	694	626	568	529
October	418	406	364	328	305
November	199	194	174	157	145
December	115	112	100	90	84

D.

Input data report from IDA ICE : Case study Building 1 & 2

EQUA SIMULATION TECHNOLOGY GROUP		**Input data Report**	
Project		**Building**	
		Model floor area	208.8 m^2
Customer		Model volume	510.0 m^3
Created by	Delluser	Model ground area	113.6 m^2
Location	Goteborg (Save)	Model envelope area	477.0 m^2
Climate file	Gothenburg, SÃ×ve-1977 (example)	Window/Envelope	5.2 %
Case	ÅSA HUS base case	Average U-value	0.5602 W/(m^2 K)
Simulated	2016-06-30 17:23:47	Envelope area per Volume	0.9352 m^2/m^3

Wind driven infiltration airflow rate			132.442 l/s at 50.000 Pa	
Building envelope	**Area [m^2]**	**U [W/(m^2 K)]**	**U*A [W/K]**	**% of total**
Walls above ground	181.25	0.44	80.20	30.02
Walls below ground	43.14	0.33	14.42	5.40
Roof	109.81	0.26	28.60	10.70
Floor towards ground	113.62	0.14	16.29	6.10
Floor towards amb. air	0.00	0.00	0.00	0.00
Windows	24.75	2.60	64.36	24.09
Doors	4.39	2.47	10.85	4.06
Thermal bridges			52.47	19.64
Total	476.97	0.56	267.19	100.00

Windows	**Area [m^2]**	**U Glass [W/(m^2 K)]**	**U Frame [W/(m^2 K)]**	**U Total [W/(m^2 K)]**	**U*A [W/K]**	**Shading factor g**
NE	7.98	2.60	2.60	2.60	20.75	0.52
SE	2.56	2.60	2.60	2.60	6.66	0.52
SW	10.75	2.60	2.60	2.60	27.96	0.52
NW	3.46	2.60	2.60	2.60	8.99	0.52
Total	24.75	2.60	2.60	2.60	64.36	0.52

Input data Report

Project		Building	
		Model floor area	150.3 m^2
Customer		Model volume	310.4 m^3
Created by	Delluser	Model ground area	81.1 m^2
Location	Stockholm (Bromma Airport) _024640 (ASHRAE 2013)	Model envelope area	312.1 m^2
Climate file	Stockholm, Bromma-1977 (example)	Window/Envelope	5.5 %
Case	Villa Katrinholm CAV	Average U-value	0.4529 W/(m^2 K)
Simulated	2016-05-13 01:16:18	Envelope area per Volume	1.006 m^2/m^3

Wind driven infiltration airflow rate			561.867 l/s at 50.000 Pa	
Building envelope	**Area [m^2]**	**U [W/(m^2 K)]**	**U*A [W/K]**	**% of total**
Walls above ground	128.48	0.27	34.82	24.63
Walls below ground	0.00	0.00	0.00	0.00
Roof	82.00	0.18	14.92	10.55
Floor towards ground	81.11	0.13	10.75	7.60
Floor towards amb. air	0.00	0.00	0.00	0.00
Windows	17.18	2.60	44.67	31.60
Doors	3.35	1.49	5.00	3.54
Thermal bridges			31.21	22.08
Total	312.12	0.45	141.36	100.00

Windows	Area [m^2]	U Glass [W/(m^2 K)]	U Frame [W/(m^2 K)]	U Total [W/(m^2 K)]	U*A [W/K]	Shading factor g
NNE	0.84	2.60	2.60	2.60	2.18	0.52
ESE	5.36	2.60	2.60	2.60	13.93	0.52
SSW	3.77	2.60	2.60	2.60	9.79	0.52
WNW	7.22	2.60	2.60	2.60	18.76	0.52
Total	17.18	2.60	2.60	2.60	44.67	0.52

E.
The detailed schedule for stochastic model regarding the occupancy, lighting and equipment:

Table 4 : Lighting schedules for different zones in the stochastic model

Zones	Time	Day
Laundry	18-18,30 pm	Saturday
Bed room 3	17,30 -18 pm & 22 -22,30 pm	All days
Familyroom	20 -21 pm	Saturday
Living room	18,30 -19 pm & 20 -21 pm	Weekdays
	18-20 pm	Weekends
Kitchen	7-7.30 am & 20-21 pm	Weekdays
	18-20 pm	Weekends

The lighting schedules has not been considered for the summer time due to the longer daylight hours

Table: 5: Occupancy schedule for different zones in the stochastic model

Zones	Time	Day
Laundry	9-9.30 am, 15-15.30 pm & 18-18.30	Saturday
Bed room 3	22 pm -7am	Workdays
	23 pm -8.30 am	Weekend
Familyroom	19 -20.0 pm	Saturday
Living room	17.30-19.0 & 20-21 pm	Weekdays
	9 -11 am &18-20 pm	Weekends
Kitchen	7-7.30 &18-20	Weekdays
	11-12 pm & 18-21	Weekends
Storage	14-14.30 pm	Weekends

Table: 6: Equipments schedule for stochastic model

Equipments	Schedule	Day
Washing machine	9 am-3pm	Saturday
Tork machine	16 -18 pm	Saturday
Tablet computer	16- 18 pm	Weekdays
	10-12 pm & 17-19 pm	Weekends
Desktop computer	18-19 pm & 20.30 -21pm	Weekdays
	15-17 pm	Weekends
Internet router	on	All day
TV	18-19 pm & 20-21pm 10-11pm & 20-21pm	Weekdays Weekends
Home theatre projector	20-21 pm	Weekends
Electric oven	7-7.30 pm & 17.30-18.30 pm	Workdays
	9-11 pm & 18-18.30pm	
Microwave Oven	18.30-19 pm	Seven days in a week
Vacuum cleaner	14-15 pm	Saturday
Laptop	18-19 pm & 20.30 -21.30pm	Weekdays
	13-15 pm	Weekends

F.

The calculation of the ground U value:

The hand calculation for the ground U value were conducted using the following formula :

$$U = \frac{2\lambda}{\pi B' + d_t} \ln\left(\frac{\pi B'}{d_t} + 1\right)$$ .... [1]

Here,

λ = is the heat conductivity of the soil/ground material [W/mK]
B´=is the characteristic dimension of the slab on ground [m]
dt= is the equivalent thickness of the slab on ground [m]

$B´$=A/0.5P .... [2]

Here,

A = is the area of the ground floor [m²]
P = is the external perimeter of the slab on ground [m]

$dt = w + \lambda(Rsi + Rfloor + Rse)$ .... [3]

Here,
dt = is the equivalent thickness of the floor [m]
w = is the total thickness of the exterior wall [m]
Rsi = is the surface resistance indoor = 0.17 [m²K/W]
$Rfloor$ = is the resistance of the floor construction [m²K/W]
Rse = is the surface resistance under the slab = 0.04 [m²K/W]

The following input values were used to obtain the result

INPUTS	VALUE
R_{si}	0.17
Rfloor	0.39
R_{se}	0.04
λ	0.45
w	0.25
A	147.74
P	54
d_t	0.52
B´	5.47

Now, using equation 1, the calculated U value of the ground is

$$\textbf{U}= \frac{2x\ 0.45}{3.1416\ x\ 5.47+0.52} \ln(\frac{3.1416\ x5.47}{0.52})\ +\ 1$$

$= \mathbf{0.17}$

Therefore, the U value of the ground according to the calculation is 0.17.

LUND UNIVERSITY

Dept of Architecture and Built Environment: Division of Energy and Building Design
Dept of Building and Environmental Technology: Divisions of Building Physics and Building Services