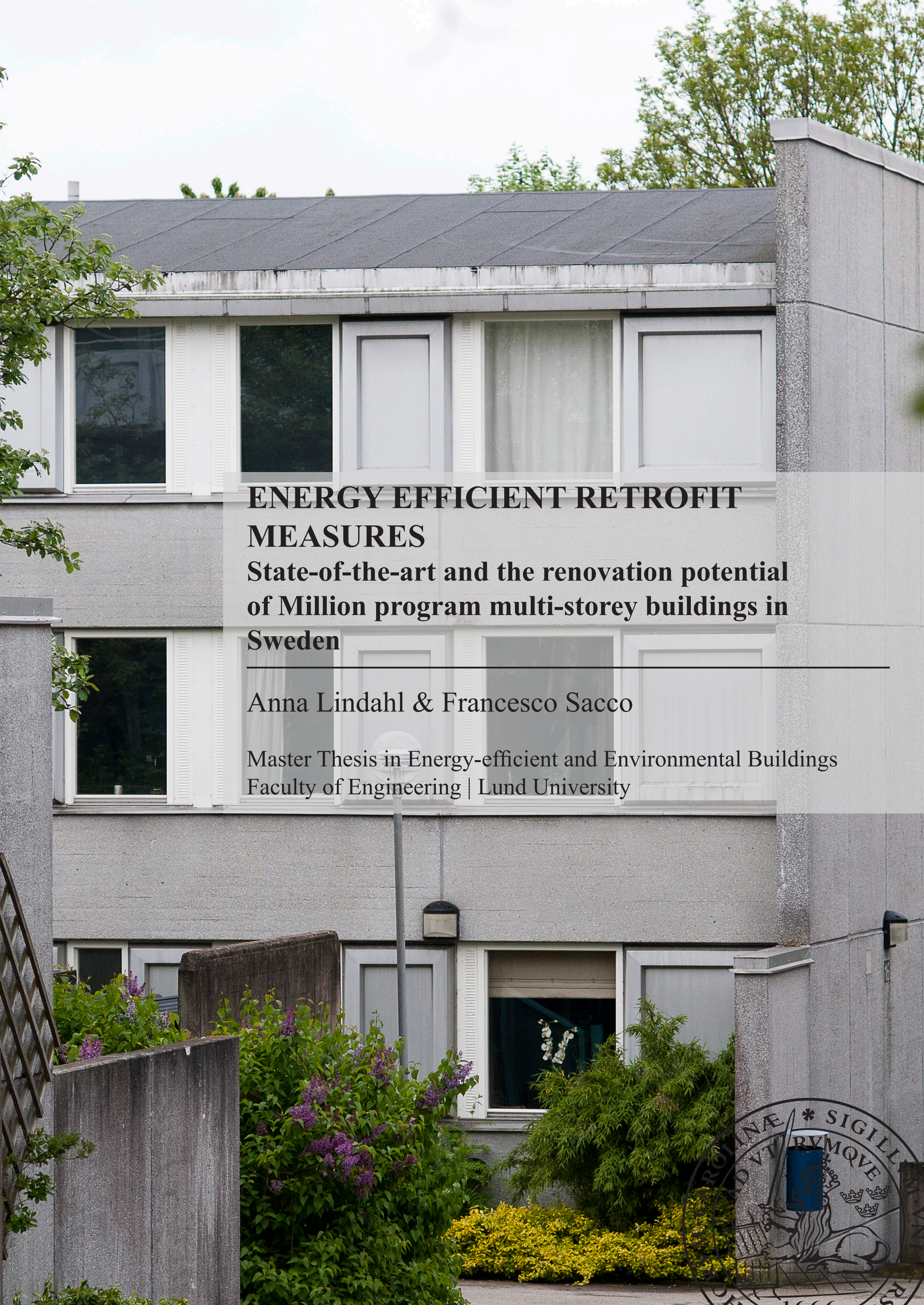

ENERGY EFFICIENT RETROFIT MEASURES

State-of-the-art and the renovation potential of Million program multi-storey buildings in Sweden

Anna Lindahl & Francesco Sacco

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: Jouri Kanters (Energy and Building Design)
Supervisor: Susanne Gosztonyi (Energy and Building Design), Linus Malmgren (Sveriges tekniska forskningsinstitut)

Keywords: Miljonprogram multi-family home, Energy efficient, Refurbishment, 2050 energy target, Renovation strategies, Building codes

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Abstract

Households and services together account for 40% of the final energy consumption in Europe. The goals set by the European Union are on the short run to reduce the greenhouse gas emissions levels by 20% by 2020. The building sector has a largely untapped potential for energy saving and a consistent percentage of the building stock has been built during the post-war economic boom years is now in need of renovation. The goal of this thesis is to demonstrate that it is possible to obtain energy savings far beyond the 2020 levels, namely 50% of the final energy consumption, when renovating a *Miljonprogram* multi-storey residential building by using technologies available on the market. This study investigates the current state-of-the-art measures for energy saving used during renovation of multi-family buildings in Europe by analysing several refurbishment projects. Drivers for renovating and barriers connected to the refurbishment process are also investigated. The renovation measures are grouped in packages (such as the replacement of windows in connection with the roof insulation), to be tested in the framework of different scenarios (business as usual, upgrading of the envelope elements to the minimum BBR 22 requirements, major renovation) with a growing level of energy savings to reach the goal. A reference building is presented and modelled to assess the impact of the proposed solution packages from the different scenarios. It is demonstrated that it is possible to reach the desired 50% reduction in energy consumption by upgrading the building envelope to the minimum requirements provided by the BBR 22 and at the same time installing a supply and exhaust mechanical ventilation system with an heat recovery efficiency of 85%.

Preface

This master thesis was carried out in cooperation with SP, *Sveriges Tekniska Forksningsinsitut,* and represents the final project of the master degree in Energy-efficient and Environmental Building Design at Lund University.

The work aims to get an insight into the renovation process and the current refurbishment measures on the European market, to apply it to the renovation of a *Miljonprogram* multifamily house in Lund to get a reduction in the final energy consumption of at least 50%.

We would like to give a special thanks to Linus Malmgren from SP, who has been our external supervisor, for his participation in this project, with his enthusiastic discussions, guidelines and advices.

Thanks to Lunds Kommunala Fastigheter AB, LKF, for providing us with the reference building, drawings and input data, and their kindness and interest in our project.

We would also like to thank Niklas Uddenäs at Strusoft AB for providing us with VIP-Energy licenses, giving us training in the programme, expert knowledge and great support during the set-up of the case study.

We would also like to thank our Supervisor at Lund University, Susanne Gosztonyi, for all the support and good guidance during this project. Thanks to the other professors at the Lund University and the Division of Energy and Building design, for the knowledge and inputs you have given us during those two years. A special thanks to Henrik Davidsson who always has time to dedicate to us students.

A special thanks to our families, for supporting us throughout the years. Thank also to Studentlund for providing us with the best time of our lives.

Lund, June 2016

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1 Introduction

1.1 Background

As the effects of climate change become more tangible every year, the efforts towards a low-carbon and energy efficient society demand intervention in every sector. Households and services together account for 40% of the final energy consumption in the EU-28 (Eurostat, 2015). The building sector plays therefore a key role in cutting the carbon emissions and win the challenges of the next decades. The goals set by the European Union are on the short run to reduce the greenhouse gas emissions levels by 20% by 2020 (European Commission, 2015) and on the long run by 80-95% (European Commission, 2015), both compared to 1990 levels.

The building sector is the biggest energy consumer in the EU and has also the largest potential for energy efficiency compared to the other sectors as industry and transport, yet it is still "the largest untapped source of cost effective energy saving and CO_2 reduction potential within Europe" (BPIE, 2014). It is only in relatively recent times that this potential has been recognized by the policymakers: In 2002 the European Parliament has issued the Energy Performance Building Directive (EPBD) (European Parliament, 2002), which required the member states to implement their building regulations and introduce an energy certification system.

The European building stock expands slowly, at a rate of about 1% (BPIE, 2011) which is also the current major renovation rate at the moment (IEA, 2013), with the aim of raising it to at least 3% by 2020. Most of the building stock is in need of renovation: About 40% of the residential buildings were built before 1960 and almost 84% are more than 20 years old (IEA, 2012). This means that most of the buildings were built with no consideration to energy efficiency and sustainability, and show also poor indoor comfort conditions and decay of the building envelope and services. Many buildings built in the economic boom years after WWII are now in need of a deep and comprehensive renovation: Since buildings have typically long renovation cycles, of about 30 years for the envelope and 20 years for the HVAC systems, it is therefore likely that there will be only one complete renovation cycle of the building stock before 2050 (Ecofys, 2012). This means that there is probably just one chance to do it right, or to fail.

1.2 Problem statement

While there is plenty regulations concerning the energy performance of buildings, which set values and benchmarks to be attained by new and existing ones, there is a lack of specific instructions on how to renovate to reach the desired conditions. Every project, due to its characteristics, can be considered as a *unicum* but there is need for guidelines for each category of building, classified according to age, climate zone and building type. The renovation process is complex and gathers different actors and stakeholders. There is no shortage of well-established renovation technologies on the market, but when it comes to select the best fitting there is lack of a broad knowledge to guide the choice. Due to this reason, the European Union is financing some research projects that aim at closing this knowledge gap, such as UMBRELLA, E-RETROFIT-KIT, EASEE, RePublic_ZEB to cite some. According to a survey conducted by Femenias (Femenias, et al., 2015), when it comes to renovation in Sweden it is often more important to provide support during the decision process in form of technical consultancy and tools rather than sole financial support.

The knowledge and experience created by implementing innovative renovation processes and solutions are not collected by authority to spread the good practice, creating confusion and a need for clear guidelines to be followed during renovation. There is no shortage of decision making tools but they are mostly intended for new buildings and have not been widely accepted yet in renovation (Thuvander, et al., 2012).

1.3 Goal and scope

The goal of the thesis is to demonstrate that it is possible to obtain energy savings far beyond the 2020 levels (20%), namely 50% of the final energy consumption, when renovating a *Miljoprogram* multi-storey residential building by using well-established refurbishment technologies available on today's market (it should be noted though that the 20% is about the greenhouse gases emission, while the 50% considered in this thesis is about the final energy consumption of the building) . The 50% is indicated by ASHRAE as the first step to reach the net-zero building goal (ASHRAE, 2016).

The renovation technologies in this thesis are available for the European context, and special focus is set on the northern climate. Since the goal is to renovate a building in Sweden: In the state-of-the-art, nonetheless, technologies for warmer climates are also described. This work is focused on the energy-saving measures, which means those that when implemented will reduce the annual energy consumption of the building. When going through the case-study buildings investigation, only those built in the post-war until the oil crisis years (1945-1975) are considered. They still represent a relevant part of the European building stock, and most of the retrofit solutions can be used anyway to renovate older buildings and newer ones. As for the reference building used in the simulation part, the most common type built during the *Miljonprogram* is chosen, but similar considerations can be applied also to other buildings of the same period.

This thesis wants to provide support for the renovation of multi-family buildings of the *Miljonprogram* era, by advising in the renovation process through suggesting several packages of retrofit solutions that could suit different stakeholders' requests.

1.3.1 Research questions

What are the present energy-saving measures used in renovation of buildings from the post-war period in Europe, and which are the motives that lead to renovation and the barriers connected to the renovation process?

Is it possible to reach a 50% reduction in the user energy consumption of a multi-family residential building from the *Miljonprogram* by applying existing energy efficient measures available on today's market?

1.3.2 Limitations

The renovation of the building stock is a complex subject, therefore some boundaries conditions had to be set. Only the phase concerning the renovation measures selection was considered, so no issues concerning commission and project management were addressed. Also, no Life Cycle Analysis (LCA) or Life Cycle Cost Analysis (LCCA) were performed under the framework of this thesis, and it is suggested to do so for further research to get a more comprehensive picture of the renovation process. The way the implemented solutions affect the tenants from a social perspective was also not taken into account.

Since this thesis does not focus only on the assessment of the energy consumption of the case study building but also on the information gathering on the renovation projects in Europe and their analysis, comfort issues were not taken into account when simulating the case study.

1.4 Methodology

To address the problem and reach the goal, both a qualitative and qualitative approach was applied, divided in the following steps:

Qualitative:

- Case study of current renovation projects, both at the Swedish and European level. Completed and ongoing projects, concerning renovation of post-war multi-storey buildings were analysed to identify and list the renovation measures, to understand the current practice

- Literature review on renovation state of the art (methods and technologies). The most used technologies, found studying the renovation projects, were listed and described by identifying the climatic area where they are used, their pros and cons and their future developments.

- Definition of the renovation scenarios, by setting up packages of the renovation measures described in the state-of-the-art.

Quantitative:

- Selection and modelling of a building from the *Miljonprogram* housing stock. The European and Swedish building stock are analysed and compared in terms of age, ownership and type, then a Swedish reference building from the *Miljonprogram* is chosen as the reference to perform the simulations on, by a statistic analysis to see which is the most common.

- Simulation of the energy performance of the building for the different scenarios and ranking according to the final user energy in terms of kWh/(m^2year).

1.4.1 Software used

The software tool used in this project is VIP-Energy, developed by Strusoft AB (Strusoft AB, 2016). A simulation model was built to calculate and analyse the energy performance of the chosen reference building. Further description of the software is presented under chapter 6.

1.5 Thesis outline

The outline of the thesis, to show how the research was conducted, is shown in Figure 1.1. Every chapter comes with a short introduction and a short conclusion to make it easier for the reader to recap the information presented in the chapter, or as a quick overview.

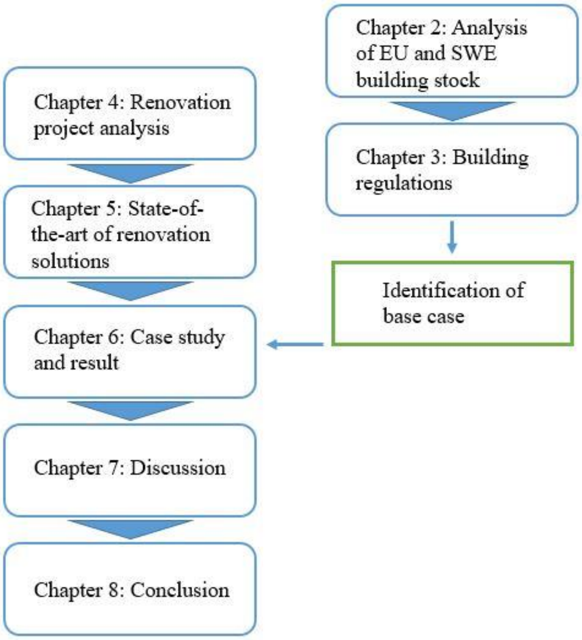

Figure 1.1. Conceptual scheme of the thesis

2 The European building stock vs. the Swedish building stock

Before collecting data concerning the renovation projects, it is relevant to understand how the subject of the study, the post-war residential building sector, is related to the existing building stock. This is analysed in this chapter in terms of age, ownership and type of buildings to see how patterns change across the European continent and to make a comparison between Sweden and Europe. The *Miljonprogram* building stock of Sweden is then further investigated to find the most common building typology, which will be the object of the simulation part.

An overview of the building regulations on energy consumption in both, Sweden and a few counties in Europe, is also made to compare different approaches and to see how they influence renovation strategies.

2.1 The European building stock

The more recent statistics about the European building stock are provided by Eurostat (Eurostat, 2015): The following data, except that concerning age, is retrieved from the Housing statistics page, which makes a summary of the complex bundle of data available on the website.

It is interesting to note that the majority of the residential floor area in the EU-27, approximately 72 %, is concentrated in six countries: Spain, Italy, France, Germany, UK and Poland (iNSPiRe project, 2014).

2.1.1 Age

The investigated literature concerning the age of the building stock is not homogeneous about the time intervals in which age is classified. The Building Performance Institute of Europe (BPIE), in its 2011 report (BPIE, 2011), subdivides age into three periods: Before 1960, between 1960 and 1991 and after 1991, due to the boom in construction of the 1960-1991 period. Data is classified in three categories: South, North & West and Central & East Europe. The buildings erected in the 1960-1991 period are between 39% and 49% of total, depending on the location. The new buildings (after 1991) are only a smaller fraction of total, between 14% and 19%, which underlines the existence of a large part of the stock in need of renovation.

A similar study was carried out within the framework of the iNSPiRe project (iNSPiRe project, 2014): Since the rate of new buildings has slowed down progressively after the 1970s, data was divided as in Table 2.1. The statistics show that more than half of the EU-27 building stock was built before 1970, meaning that there is a great retrofit potential still untapped. It can also be noticed how the building rate has decreased steadily after the boom years.

Table 2.1. Percentage of built stock in Europe according to age

Year	Before 1970	1971-1980	1981-1990	1991-2000	After 2000
% of built stock	53%	15-18%	12-13%	11-12%	6-7%

Meijer et al., 2009 carried out a research with an age subdivision that suits the purpose of this thesis. They considered eight countries and classified the buildings according to the following age intervals: Before 1919, 1919-1945, 1946-1970, 1971-1990 and after 1990. The age distribution varies throughout the different countries, but the buildings erected in the post-war period 1946-1970 represent a consistent percentage, from just below 20% in France up to almost 45% in Germany. Given the figures, the renovation of post-war buildings is therefore relevant through Europe.

2.1.2 Ownership

Statistically, building ownership can be divided in three main categories: Owner occupied, private rented and social rented (Itard, et al., 2008). The building ownership is a factor that influences the renovation process, due to the landlord/tenant dilemma: Both landlords and tenants are interested in how much energy is consumed by the building and about the living standard. When it comes to renovating, someone has to pay for the necessary works. If the dweller owns the house, the owner will pay to retrofit it and will see the benefits, so this might be encouraged to do it. The problem is due to the fact that the landlord might be reluctant to pay for the renovation works that will protect his long-term investment in the property, while the tenant might also be unenthusiastic about incurring in short-term costs but will be the one benefitting directly from renovation and the consequent lower energy bills. The problem is starting to be addressed in some countries such as France and Germany with targeted “split incentives” in order to encourage landlords to implement renovation projects (CEPI - UIPI, 2010). This problem is even more accentuated in the case of social housing, where the rent are kept low by the municipalities and therefore it is usually hard to increase the rent to repay the renovations undergone on the building due to the limited financial means of the tenants (RESHAPE, 2009).

Figure 2.1 shows the figures collected by Eurostat (Eurostat, 2015), which differentiates between owner occupied with an ongoing mortgage or not. Once again, the figures vary between countries: Those who have a large part of the building stock for rent, amongst which Austria (40% rental), France (42%), Germany (54%), Netherlands (48%) and Sweden (37%) (iNSPiRe project, 2014), will be more affected by the landlord/tenant dilemma. The EU-28 average is about 70% of owner occupied dwellings.

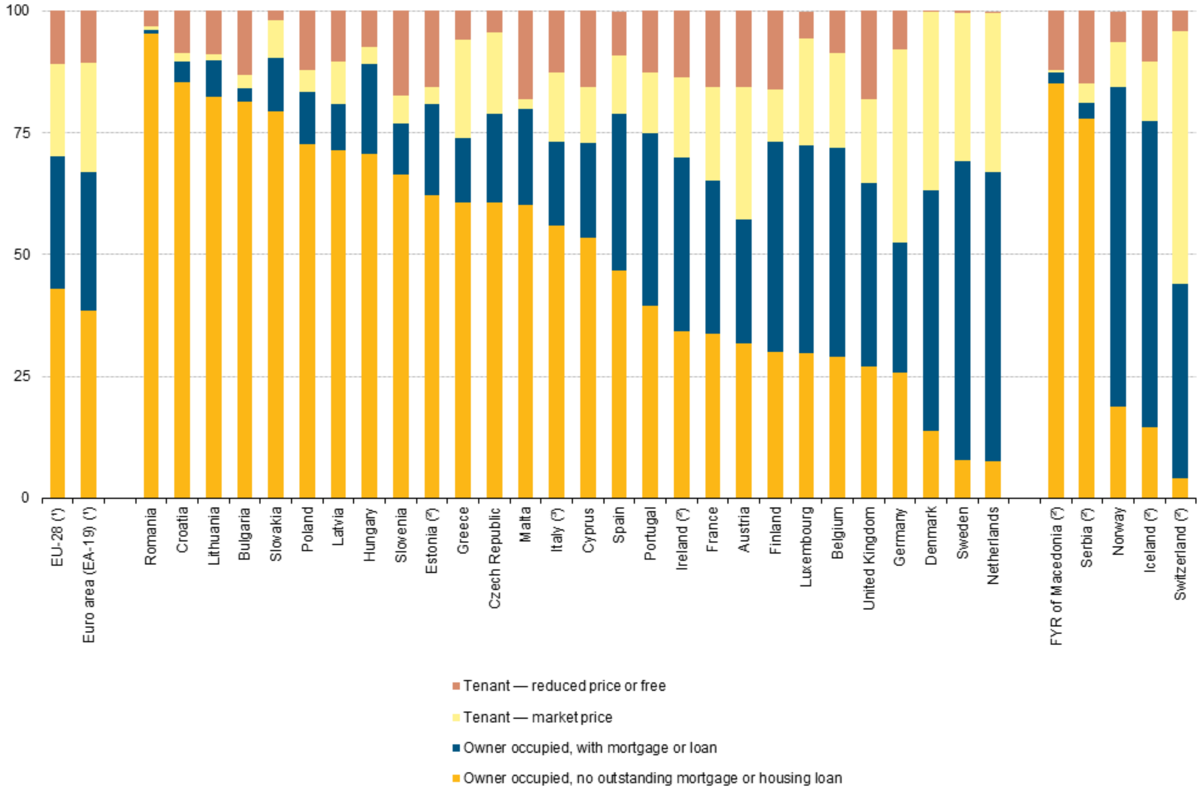

Figure 2.1. Distribution of population by tenure status, 2014 (% of population) (Eurostat, 2015)

In Sweden the situation is particular since heat is included in the rent, and most of the social housing is owned by so-called *allmännyttiga bostadsföretag*, which translated means companies that work for the "public benefit". Those enterprises have the goal of just managing their stock for the community, without making profits. It is therefore easier to renovate when the dwellings are owned by the same actor, but at the same time the rents cannot be raised excessively to repay for the renovation works, which is one of the biggest challenges that the Swedish government will have to face in the coming years (Berglund, 2009).

2.1.3 Type

The type of dwelling affects the renovation process from an economical point of view: Since multi-family buildings are more compact (more inhabitants per square meter) and bigger than single-family ones, their renovation is more cost-effective and therefore more attractive (iNSPiRe project, 2014).

Eurostat makes the subdivision in flats, detached and semi-detached houses, while the survey conducted by the iNSPiRe project simplifies and classifies the dwellings in single- and multi-family buildings. Figure 2.2 shows the statistics provided by Eurostat: Once again, the figures vary greatly across the different countries. In 2014, 40% of the people in the EU-28 lived in flats, about 25% in semi-detached houses and 33% in detached houses.

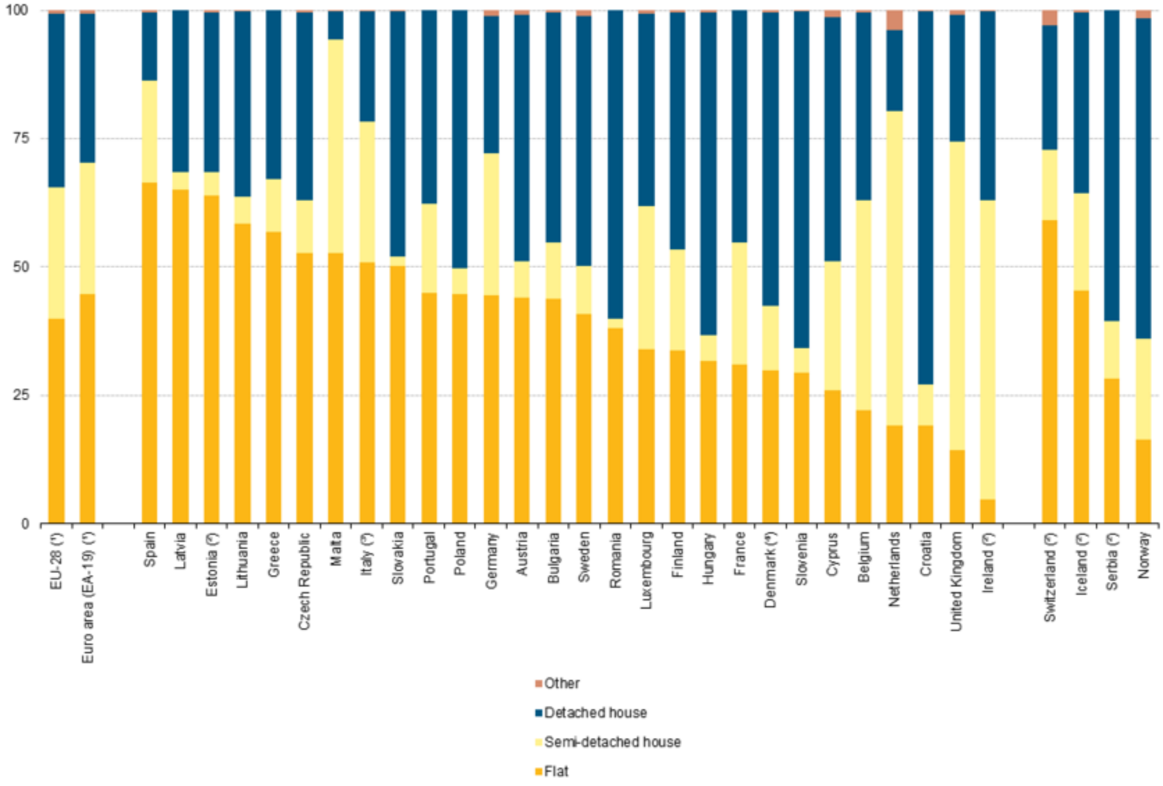

Figure 2.2. Distribution of population by dwelling type, 2014 (% of population) (Eurostat, 2015)

2.2 The Swedish building stock

Sweden's building stock is characterized by the so called Record Years, where a million dwellings (both in multi-family and single-family buildings) were built within ten years between the 1960s and 1970s. After 1990, the construction activity collapsed and has lain low due to the 2007 financial crisis. After 2010 it has recovered and it is now increasing again, spurred by the lack of dwellings, a problem now endemic in Sweden (Olofsson, et al., 2015).

2.2.1 Age

The data retrieved from the Statistiska Centralbyrån for the age of dwellings (Statistiska Centralbyrån, 2016), updated for 2014, is summarized in Table 2.2.

Table 2.2. Number of single- and multi-family buildings in Sweden

Year of construction	**Number of Single-family**	**Number of Multi-family**	**% of total single-family**	**% of total multi-family**
-1930	406 659	201 137	20.3	8.6
1931-1940	140 623	152 529	7.0	6.5
1941-1950	137 415	239 254	6.9	10.2
1951-1960	163 531	393 579	8.2	16.8
1961-1970	288 531	579 053	14.4	24.7
1971-1980	426 581	296 765	21.3	12.7
1981-1990	212 262	193 788	10.6	8.3
1991-2000	97 326	125 508	4.9	5.4
2001-2010	107 299	109 411	5.4	4.7
2011-	21 288	52 114	1.1	2.2

It can be noticed that the buildings erected in the period 1950-1970 represent 22.6% of the single-family and 41.5% of the multi-family stock, reflecting the huge building activity of the Record Years.

2.2.2 Ownership

As for the type of ownership, data from Statistics Sweden is subdivided in three categories: *Hyresrätt*, *bostadsrätt* and *äganderätt*. *Hyresrätt* means that the resident is the tenant, for the second one *bostadsrätt* the tenants are partly owners while the last one *äganderätt* is the residents the owner of the house. The Statistics Sweden considers also "special houses" for this classification along with the single- and multi-family houses, which are residences for the elderly persons and student accommodations. In order to make a similar classification to the Eurostat one, the *bostadsrätt* and *äganderätt* categories are considered as one, namely owner occupied, and *hyresrätt* as tenant occupied. Data is shown in, updated as 2015 (Statistiska Centralbyrån, 2016).

Table 2.3. Distribution of dwellings in Sweden according to ownership

All kinds of dwellings	**Number of dwellings**	**Multi-family houses**	**Number of dwellings**
Hyresrätt	1 801 248	Hyresrätt	1 419 730
Bostadsrätt	1 064 629	Bostadsrätt	967 938
Äganderätt	1 849 287	Äganderätt	803
No data	1 404	No data	100

The table shows that 38.2 % of the dwellings in total are occupied by tenants, while 61.7 % are owner occupied (data does not add up to 100 since there are some dwellings for whose ownership is unknown). When looking only at multi-family houses, percentages become respectively 59.4 % and 40.5%. It should be noted that the Eurostat statistics consider the percentage of the population, while the Swedish Statistics consider percentage for the dwellings. The percentage of owner occupied buildings is lower than the EU-28 average (61.7% vs. about 70%).

2.2.3 Building typology

There are 2 018 064 single-family (*småhus*) and 2 388 571 multi-family buildings (*flerbostadshus*) in Sweden as of 2015 (Statistiska Centralbyrån, 2016), which represent 46% and 54% respectively of the residential sector. For single-family, detached and semi-detached one- and two- family houses, plus terraced houses, are considered. As for multi-family houses, they are buildings with three or more apartments. This is different in comparison with the EU-28 average (about 40% of the population living in flats), but once again the Swedish figures are calculated on the number of dwellings while the European ones on the share of population living there.

2.3 The Swedish *Miljonprogram* and the present housing market

Between 1965 and 1974, 1 005 578 dwellings were built in Sweden: This is commonly referred as the *Miljonprogram*, even though there was no real "program" to increase the construction rate, since it had been rising steadily since WWII. The term is used to refer to the goal of further increasing the production of buildings, by taking advantage of the new industrial techniques to build and produce buildings in a more rational way (Boverket, 2014).

The peak was reached in 1970: after this date, the production rate dropped as the waiting queues for apartments did not exist anymore at that time, given the exceptional availability of new-built houses. It is quite ironical that, when the administrative machine was finally capable to take care of such a large scale building construction (around 1970), the demand decreased drastically. Such an abrupt decrease in construction set a well-defined mark to the Record Years period. It might be thought that such great volumes were recklessly built, but there were actually architectural competitions and the subject was broadly discussed in journals and forums, especially on industrializing and rationalizing. Even though the buildings are not particularly attractive (simple geometrical figures with undecorated facades) and often the outside area is poorly planned and not functional, the buildings itself represented a dramatic increase in the housing standard (Hall & Vidén, 2005).

The problems of overcrowding and lack of bathrooms were solved almost completely: The Swedes benefited from the usually well-designed and equipped houses, with good materials and lots of daylight thanks to the big windows. Today those buildings are in the phase of their age when some parts and systems have reached the end of their lifetime, such as water and sewer piping. It is time to either renovate or replace those building components, exploiting at the same time the chance to improve the energy performance and indoor comfort. There is not a common state in which the buildings are today, since it depends on the renovation they have undergone through the years and the way they were built. (Vidén, 2012).

2.3.1 The Miljonprogram multi-storey buildings

The thought of a *Miljonprogram* buildings often evokes an idea of a grey, anonymous, prefabricated-concrete like multi-storey building. Actually, buildings came with a great variety of forms and concepts, both for the detached houses and flats (Hall & Vidén, 2005). This thesis focuses on the multi-storey buildings, therefore the single-family and terrace houses will not be described. There are mainly four types of multi-storey buildings that were built under the *Miljonprogram* (Vidén, 2012):

- *Lamellhus/skivhus:* This is the most common type, with a great variety of storey numbers, up to seventeen. 85% of the dwellings built in multi-storey buildings during the *Miljonprogram* are *lamellhus*, and about 65% of those houses possess between two and four storeys. The most common type is with three storeys (Boverket, 2014). If it has four storeys or more, a *lamellhus* is usually referred as a *skivhus* (Wikipedia, 2016). The typical features are band windows and low-pitch gable roof for *lamellhus*, flat roofs with internal drainage and room-wide balconies that divide the façade for *skivhus*. Figure 2.3 shows a typical lamellhus in Lund.

Figure 2.3. Typical lamellhus in Linero, Lund, reference building for this thesis, built 1972

- *Punkthus:* This type of house has from three to sixteen stories and represent 10% of the total number of dwellings built under the *Miljonprogram*. A single staircase centrally situated in the building, with the apartments grouped around, usually characterizes them. No eaves and sheltered balconies are also common features. Figure 2.4 shows a typical *punkthus* in Farsta.

Figure 2.4. Typical punkthus in, Farsta (Johan Rådberg, 2012)

- *Loftgångshus:* It is a two to eight storeys, built mainly in the 1970s (Bernjaro & Pedram, 2012). They are the least common type, representing about 5% of the dwellings built as multi-family houses during the *Miljonprogram*. As the Swedish name suggests, the characterizing feature is that the apartments are reached through external corridors on the long side of the building. The corridors itself are connected to an external staircase, representing a block outside the building. The idea behind this concept was to promote the socialization between neighbours, but the external corridors has the side effect of minimizing the amount of daylight and reduced privacy. Figure 2.5 shows a typical *loftgångshus* built in the early 1970s.

Figure 2.5. Typical loftgångshus in Möllevång, Lund, built 1964

2.4 Building requirements and characteristics from 1950 to 1970

Having a colder climate than most of the other European states, Sweden started earlier to implement a building code system, which set requirements about ventilations, hygiene and insulation. An interesting analysis was performed by VVS Företagen (2009) where the evolution of the building codes and architectural solutions from 1950 to 1975 is described. A brief recap is reported in the following subchapter to understand how the requirements of that time influence the present building performance and how the building solutions affect the necessary renovation process.

2.4.1 Houses built during the 1950s

The first regulation came out in 1946, with the so called BABS (*Byggnadsstyrelsens anvisningar till byggnadsstadgan)* (Boverket, 2014), followed by a new version four years later, the so-called BABS 1950 (Boverket, 2014). Sweden was divided in four climate zones, and for each there were requirements concerning the maximum U-value of walls, roofs and basement floors, as well as the ventilation flow in rooms, toilets, kitchen and bathrooms, in terms of cubic meters per hour and extraction area.

During these times, the traditional, construction methods were applied: Windows were small, double-glazed with good quality wooden frames, and the facades were either plastered or with tiles. Roofs are pitched and the covering is made of tiles, often with roofing felt or asbestos. It is usually the external walls, made of light concrete blocks that have the load-bearing function. After the war years, there was greater awareness concerning thermal insulation: During the 1950s started the production of self-sustaining mineral wool panels.

The heating was provided mostly through central heating or, more rarely, district heating; oil heating started to spread from the 1940s. The water culverts in the cellars were poorly insulated. Copper, already used for domestic hot water piping, starts to be used also for cold water piping. During those years, progress was made in the building systems, as thermostat valves made their debut. Ventilation is natural, with the intake under the windows and the outtake in toilets and kitchens. Taller buildings have fans in central ducts to extract the exhaust air.

2.4.2 Houses built during the 1960s

BABS 1960 set the minimum requirements for U-values of the envelope and ventilation (Boverket, 2014). It can be observed that the maximum U-values are lower (about 10%) than those in BABS 1950, while the ventilation rate is the same. The envelope had to be made in a way to avoid condensation problems and draughts.

Prefabricated elements started to be used: The technological innovations that started in the former decennium were now established. There was a transition from load-bearing to non-load-bearing external walls, which meant that prefabricated façade modules could be produced in series, transported and mounted on the building structure. Typical prefabricated facade panels are either 25 cm plastered light concrete blocks, sandwich panels with (outside to inside) 5 cm concrete, 10 cm mineral wool and 10 cm concrete, or also panels with wooden studs, 10 cm of mineral wool and external cladding.

The more industrialized construction method caused a worse air tightness and accentuated thermal bridges, and the insulation was poor.

Heating was usually provided by centralized oil boilers, with a water radiators distribution system. Exhaust ventilation became more popular, and towards the end of the decade, supply and exhaust systems started to be installed. Copper was still used for hot and cold water piping.

2.4.3 Houses built during 1970-1975

In 1967, the SBN 67 (*Svensk byggnorm*), also called BABS 67, was published, whose requirements became mandatory from June 1968 (Boverket, 2014). The requirements about the U-values are the same as for BABS 60 (the breakthrough will come later with SBN 75 after the 1973-1974 oil crisis).

The building typology and materials are more or less similar as from the last years of the previous decade: Buildings became wider and some rooms were left without daylight access.

District heating became more common: The heating centrals were replaced by connections to the local district heating network. Supply and exhaust ventilation systems became also increasingly more popular, though without heat recovery.

2.5 Conclusions

The Swedish building stock is in line with the European building stock (single- vs multi-family), even though data for the Swedish stock is collected as building numbers and for the European as percentage of population. Sweden has a lower share of dwellings owned by those who are living in than Europe (data collected as for typology). The buildings erected in Sweden in the period 1950-1970 represent 22.6% of the single-family and 41.5% of the multi-family stock. Data for Europe shows that more than half of the buildings were built before 1970: The number of aging buildings is high and the potential for energy saving through major renovation remarkable.

The Swedish housing market is going through a crisis due to a lack of dwellings in the bigger cities area, a combination of higher wages, rapidly growing mortgages and low interest rates keeping the prices unreasonably high, and a taxing system that makes it very costly for people to move, creating a matching problem and greatly reducing the offer. This stalemate can be solved by addressing those economic and market structure issues at the same time, but it requires a deep system change.

The *Miljonprogram* houses are now in great need of renovation, since many of their components and materials reached the end of their lifetime. They were built in an era when there were already regulations in Sweden setting value limits for the thermal transmittance of the envelope, even though they cannot be compared with today's requirements. As a result, buildings are very poorly insulated or not insulated at all in comparison to the current standards. Since renovation would need to be performed anyway, it is a unique chance to apply some energy efficient retrofit measures as well, which is cheaper than doing it in a separate intervention.

As shown the three-storey *lamellhus* stands for 85% of all the dwellings that was built during the *Miljonprogram*. According to the statistics, this is the most common multi-family building and there for this is chosen as reference building, to apply and analyse simulations for energy efficient solutions. The same study could be performed to find the most common type of multi-family house in every European country.

3 Building regulations

When constructing or renovating a building, it is mandatory to follow the building codes. They are devised and implemented to regulate the construction/renovation process by providing guidelines and advice on the minimum requirements for the construction of new buildings or retrofitting of existing ones. Their aim is not only to set goals but also to provide a way on how to reach them.

Building codes has been evolving for a long time, concerning mostly construction rules to guarantee fire safety and avoiding collapse of buildings. It is in recent times, especially after the 1973 oil crisis, that engineers and architects have started focusing on energy consumption issues, by introducing minimum requirements on the building envelope elements. Those issues were already known in the Scandinavian countries, where governments set standards for thermal insulation (although not as stringent as today) already in the 1950s and 1960s, not out of environmental consciousness but rather to tackle the health problems caused by the poor housing conditions and also to increase the indoor comfort in the economic boom period. As today, the building codes and regulations exist in almost all the OECD countries, even though there are consistent differences between the states, both in terms of requirements and calculation methodologies (IEA, 2008).

Building codes are usually made of different parts: The requirements on energy efficiency can be a chapter in the building code, usually giving concise instructions and referring to the specific standard, which is more comprehensive and detailed. It depends from country to country how much information from the standard, as well as methods to calculate a certain value, are included in the building code.

Along to the building codes, there are certifications and there are different labels, assess the amount of energy that the building needs, to provide standard comfort conditions to the occupants. To compare the performances of different buildings and to know at a glance whether the level of energy efficiency is high or not.

3.1 Types of regulations

Setting up regulations to limit the energy consumption of a building can be done in different ways, each with its pros and cons. Regulations can be divided in two main groups: Prescriptive and performative. (IEA, 2013).

3.1.1 Prescriptive regulations

The idea behind the prescriptive regulations is that every component of the building, especially the envelope, has to satisfy minimum requirements. For instance, a certain kind of wall cannot have a thermal transmittance greater than a fixed set point. In simpler versions, there is a list of the most important components of the building, such as the thermal transmittance of envelope parts and efficiency of heating and cooling system. In more complicated building codes, the list of requirements can be long since it applies to every component, including the minor ones such as fans and lights. This approach is very simple and easy to follow, but leaves little room to the designer to experiment new solutions.

A greater degree of freedom is provided by the trade-off system: Some components can be below the set standard as long as some others exceed it. A simple calculation method is provided along with the regulation, so that it is possible to calculate the overall value and compare it with the limit. By doing so, the designer has more flexibility in planning: The trade-off is usually made between the HVAC system and the building envelope, allowing, for instance, a building with a very efficient heating system to have a below-optimal envelope.

3.1.2 Performance regulations

Those regulations are more complex than the prescriptive ones and require a greater level of expertise. There are three different categories, in order of complexity (IEA, 2008):

- Model building: It is based on the simulation of two buildings, one with the maximum allowable values for the building components (envelope and systems) and one with the actual ones. The energy consumption is then calculated according to a precise method: If the actual building performs better than the reference, it satisfies the regulations. It is a more advanced version of the trade-off method, since a performance calculation is made. Greater flexibility is allowed, especially to make cost-effective changes that result in the same efficiency of more expensive ones.

- Energy frame: A very similar method to the previous one, it considers the overall thermal transmittance per unit area or volume of the building (such as square meter of heated floor area). By doing so, a maximum value of energy loss for the building is set.

- Energy performance: The building is simulated by taking into account all the factors that influence the performance of the building in reality, such as solar gains and losses. This method establishes the energy consumption of the building calculated in terms of primary energy or environmental indicators (such as carbon dioxide emissions) and considers the relation between produced and consumed energy. It is the most complex method, but also the one that allows the designer the utmost freedom in implementing the best solutions for the case. This method is the most complicated of all, since it has to consider many different factors.

Mixed or hybrid approaches are also possible. They usually set some maximum requirements on the U-values of the envelope components along with a limit for the energy consumption of the building. Sometimes alternatives are provided, so that the constructor can choose which regulation he considers easier to achieve with the least effort (IEA, 2008).

Today the building codes are in a transition phase from prescriptive to performative: The new challenge posed by the Nearly Zero Energy Buildings (EU Commission, 2016) require a deeper understanding of the energy behaviour of the building and therefore requires sophisticated simulation programs. The prescriptive regulations usually offer short-term economic benefits, but they might over-optimize some components, increasing the costs for energy efficiency on the long run. Their strength lies in their simplicity, while the performance based regulations support the use of complicated software that only a trained professional can master.

3.2 State of regulations in Europe

The European Union developes with directives that have to be subsequently accepted and implemented by the member states, within a certain amount of time. The directive concerning buildings is called “Energy performance in Buildings” (EU Commission, 2010), issued for the first time in 2002 and constantly updated. It gives the member states guidelines to implement it and therefore freedom to choose how far to go with the energy efficiency, but also the obligation to revise the regulations every five years to keep updated with the technological improvements. The member states can also choose how to calculate the different parts concerning energy performance, as long as existing European standards are taken into account. However, procedures can be different from one country to another, so standards are being developed to unify the procedure. Trying to compare the requirements across different EU member states would be difficult, since the calculation methods used to set the minimum requirements or thresholds usually vary in the various countries (ENTRANZE , 2014). There is also no common basis concerning the definition of values such as final energy, heated floor area etc., which tips further the comparison scale, making a common assessment impossible.

The countries where the requirements are the most stringent are the Scandinavian ones, due to the severe winter weather conditions. When considering the overall envelope thermal transmittance value, the strictest building code is the Swedish one, followed closely by the Danish and Norwegian (IEA, 2008).

It is worth noting that the EU building directive, EPBD (EU Commission, 2010) addresses mainly the new constructions; at first, for refurbishment, standards were set only for major renovations of buildings with a floor area greater than 1000 square meter, a threshold that was later lowered to 250 m^2 (ECEEE, u.d.). The recast of the 2010 EPBD clearly states that “*Member States shall in addition take the necessary measures to ensure that when a building element that forms part of the building envelope and has a significant impact on the energy performance of the building envelope, is retrofitted or replaced, the energy performance of the building element meets minimum energy performance requirements in so far as this is technically, functionally and economically feasible*” (EU Commission, 2010). The EU set also goals for a 3% annual renovation of public buildings, owned by the central government, as a measure to set benchmark examples for a more comprehensive renovation of all types of buildings at a national level (BPIE, 2016).

3.3 Building regulations in Sweden

A brief history of the building regulations development in Sweden can be found in Chapter 2.5. In the following paragraph, the current regulation is recapped by highlighting the most relevant points relevant to energy retrofitting.

BBR 22 has 9 chapters (Boverket, 2015). It contains prescriptions and advice for constructing or renovating a building, concerning room height, accessibility, noise, fire protection, safety etc. BBR´s Chapter 9 concerns the energy consumption. The previous regulations considered three different climate zones, which have become now four to account for the climate of southern Sweden, with a tightening of the maximum energy consumption due to the milder weather conditions there. The different zones are shown in Figure 3.1, while Table 3.1 reports the maximum energy consumption.

Table 3.1. Maximum energy consumption for the different climate zones according to BBR

Climate zone	**Energy consumption multi-family buildings (kWh/m², A_{Temp} annually)**	
	BBR	
	Not electric heated	**Electric heated**
I	115 (0.40)	85 (0.40)
II	100 (0.40)	65 (0.40)
III	80 (0.40)	50 (0.40)
IV	75 (0.40)	45 (0.40)
The values in brackets are the max average U-Value of the total building envelope, Uw (W/m²K)		

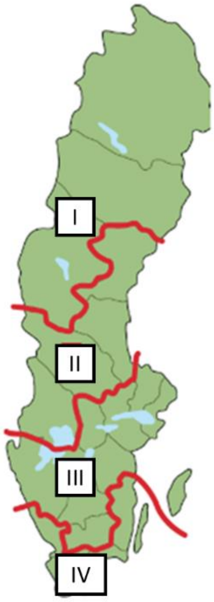

Figure 3.1. Climate zones in Sweden

With *energy consumption*, it is defined as the sum of energy used for space heating, cooling, DHW and to run the building service systems (electricity for pumps, fans and other components): this is the final energy considered in the simulations. The plug load, namely that for lighting and house appliances, is not taken in consideration. The Swedish building code is an representative example of a performative regulation, which sets values for the maximum energy consumption, combined with a prescriptive, trade-off regulation: There is a maximum value for the average thermal transmittance for the building envelope, 0.4 W/m²K, calculated by taking into account the different envelope components plus the thermal bridges. It should be noted that there are two categories, namely electric heated and non-electric heated buildings: The former have more stringent requirements concerning the maximum yearly energy consumption. Those values are for both new and refurbished buildings: If the building is only partly refurbished and therefore not reasonable to reach the values imposed by the building code, the maximum thermal transmittance values for single envelope elements shown in Table 3.2 have to be followed (Boverket, 2014). Either this values is used but it can also be used as an alternative to the energy consumption limits or overall U-value shown in the previous table. The building must also achieve an airtightness of maximum 0.6 l/s per square meter of envelope area. (Boverket, 2015)

Table 3.2. Maximum envelope transmittance values according to BBR

U-value (W/m^2K)	Non electrical heated building	Electrical heated buildings with A_{temp} 51-100m^2
U_{roof}	0.13	0.08
U_{wall}	0.18	0.1
U_{floor}	0.15	0.1
$U_{windows}$	1.3	1.1
W_{door}	1.3	1.1

3.4 Barriers

The implementation of energy efficient measures in buildings in the EU is hindered by many factors, especially in the construction of new ones. A brief list describing the main barriers to the implementation of effective building codes is described below, as reported by IEA (2013):

- Fragmentation of the building sector: There are many stakeholders involved in the process, who have different interests, often conflicting, and different knowledge in the energy efficiency issues. A lack of leadership completes the picture.
- Absence of baseline information: Without solid data basis to establish the baseline, policy makers have a hard time developing a strategy to promote energy efficiency.
- Disjointed governance structure: Implementation and enforcement of the building codes are usually the responsibility of different authorities. Few countries have a coordination level that allows the reciprocal to be understood from both sides, at national and regional level.
- Lack of technical expertise: One of the most limiting barriers, for the design and successful implementation of building codes is a deep knowledge of building sciences. This is necessary, but there is a lack of professionals and adequate training programs.
- Lack of financial resources.
- Building codes are weak without a proper enforcement. Governments and authorities shall make sure that regulations are followed, by implementing a system that provides incentives but also penalties for not complying with the latest requirements set by the building codes.

3.5 Future of building regulations

As indicated in the previous paragraphs, building codes are dynamic matters that keep progressing, taking into account new technologies and objectives that get more stringent with time. The IEA (2013) has identified three ways to which the current traditional approach is heading, briefly described below:

- Increase the factors that determine the energy consumption of buildings: New building codes will provide guidelines towards low energy buildings, by implementing energy sufficiency measures (to decrease the need for heating, cooling and lighting), energy efficiency measures (to reduce the amount of energy needed for heating, cooling and lighting) and finally, the use of renewable energy sources.
- Creating more policy instruments complementary to building codes: The building will not be seen anymore by the building code as an isolated system, but rather integrated in the socio-economic context and local environment. The aim is to reach objectives of economic development, energy security and environmental protection.
- Addressing the challenges and opportunities that originate from the long lifespans of buildings: Building codes will have to provide specific guidelines on how to renovate buildings, given their long lifetime. Implementing energy efficient measures on the perspective of maintenance works is very cost-effective and therefore a unique chance to be exploited.

The regulations will become more stringent with time, aiming eventually to the higher efficiency levels set by certifications and standards such as Low Energy Buildings, Passive House, Zero Energy / Zero Carbon Buildings and Plus Energy Buildings.

3.6 Conclusions

Building codes, at least in Europe, comprise nowadays various sets of regulations, guidelines and recommendation to reach energy efficiency in buildings. Their effectiveness is guaranteed provided that, (a) they are properly implemented, (b) there is a strict enforcement system that ensures their application and (c) that they are well aligned with the other policies that do not address directly the building but concern its energy consumption, in order to avoid contrasting directives. (IEA, 2013)

The easiest to use regulations are the prescriptive ones, by providing a list of minimum requirements for the envelope and systems. Performance regulations involve the use of a simulation software to calculate the energy consumption of the building and are therefore more holistic but also more difficult to handle.

The European Union issues and updates the Energy Efficiency Directive, a law that has to be implemented by the member states. The EU member states have some freedom to choose the methods and calculation strategies, as long as they refer to accepted international standards. This results in some differences between the building codes, since every member state develops its own methodology. When renovating buildings in different countries, it is necessary to follow the specific national building code, which means to learn a new set of specific rules, even though the core concepts are the same from the EPBD. Sweden is the country with the strictest regulations concerning the envelope, followed by Denmark and Norway.

Building codes get stricter as new technologies are introduced and as the awareness for environmental issues and energy security gets more widespread. The final aim is to reach higher energy efficiency standard, such as the Passive House or (Nearly) Zero Energy Buildings. Building codes are mostly addressed to new buildings, but in the most recent versions, renovation has gained importance with dedicated regulations specifically intended for the refurbishment process.

When renovating the case study building, the guidelines imposed by BBR will be followed, especially concerning the envelope thermal transmittance values when replacing components such as windows.

4 Renovation projects in Europe

In order to understand which renovations measures are applied as best practice in current projects, a search was performed on completed or ongoing projects in Europe concerning the renovation of multi-family post-war buildings. For every project, the energy efficient retrofit measures were listed in a table. This does not suppose any statistical relevance, due to the small number of cases considered, but rather to help identify a list of possible solutions. This will be used for the definition of renovation packages in Chapter 6, whose efficiency is to be assessed when applied to the reference building.

The project research was also meant to get some insight into the driving forces behind the renovation, which is presented in Chapter 4.4. To understand why it has been decided to renovate and which stakeholder took the initiative, since those are factors that directly influence renovation. The aim was also intended to get some "lessons learned" from the studies, to enrich the knowledge about the potential difficulties and hindrances that might affect the renovation of the considered buildings.

4.1 Methodology

The renovation projects were all found on the internet, in form of publications, reports and articles. The search engine was Google, and the keywords "renovation projects", "refurbishment projects", "building renovation", etc. Only the projects reporting a satisfying amount of information concerning the solutions that were implemented during the refurbishment were considered. Only renovation projects of buildings erected between 1950 and 1975 were taken into account, since the purpose of this thesis is to apply the renovation measures to a *Miljonprogram* house. The collected material was mostly in English but due to the relatively low amount of information found, projects of which the material was in other languages were also investigated in order to find as many solutions as possible. The countries from which the projects come are following: Sweden (SE), Germany (GER), France (FRA), The Netherlands (NL), Italy (ITA), Spain (SPA), Switzerland (SZ), Austria (AU), United kingdom (UK) and Slovenia (SLO).

For every project, the implemented solutions were written down in a list: to get an overall overview, the projects were afterwards collected in a table, with each row corresponding to a project and each column to a renovation measure. The cell in the sheet corresponding to a certain solution is ticked if that measure was used in the project, as shown in appendix A. It should be noted that only the solutions having an impact on the energy consumption of the building were considered. A more simplified list is reported in the following paragraph. The projects are categorised according building type, age, renovation solutions and country (an analysis of the building typology and age across Europe was performed in Chapter 2).

4.2 Project analysis

The renovation solutions are listed in Table 4.1, each one was assigned a letter to make an overview of which were used in the projects in Table 4.2. Each project is classified according to the country of origin, type and year of built.

Table 4.1. Renovation solutions

Solution ID	**Renovation solution**
A	Envelope insulation
B	Windows/door replacement or modification
C	External shadings (blinds/overhang)
D	Cool/green roof
E	Elimination/reduction of thermal bridges
F	Air tightness improvement
G	Mechanical ventilation (supply + extract)
H	Heat recovery on ventilation
I	Night ventilation
J	Heat pump (air/air, air/water, geothermal)
K	Solar thermal
L	PV
M	Condensing boiler
N	Small additional decentralized heating units
O	Centralisation of heating
P	District heating
Q	Thermal storage
R	Building Energy Management System
S	Radiators system upgrade
T	Lighting

Table 4.2. Overview of the projects studied

Project ID	Country	Type	Built	Renovation solutions ID	Reference
1	SPA	Multi-family	1960	A, B, C, F, J, K, O, Q, S	(Dipasquale, et al., 2015)
2	GER	Multi-family	1954	A, B, K, M	(Power & Zulauf, 2011)
3	GER	Multi-family	1974	A, B, P, S	(Power & Zulauf, 2011)
4	GER	Multi-family	1950	A, B, G, H, J, O	(Power & Zulauf, 2011)
5	GER	Multi-family	1950	A, B, G, H, S	(Power & Zulauf, 2011)
6	GER	Multi-family	1960	A, B, G, N, O,	(Power & Zulauf, 2011)
7	ITA	Multi-family	1978	A, K, L,Q	(Gagliano, et al., 2013)
8	ITA	School	1962	A, B, C, D, J, K, L, N, R, T	(Cumo, et al., 2014)
9	SPA	Multi-family	1960s	A, B, C, F, I	(Suárez & Fernández-Agüera, 2015)

10	ITA	Multi-family	1964	A, B, G, H, J, S	(Veronese, 2011)
11	ITA	School	1960s	A, B, I, K, L,	(Esposito & De Sensi, 2007)
12	UK	Semi-detached	1960s	A, B, E, F, G, H, K, L	(Low energy buildings database, 2010)
13	ITA	Multi-family	1953	A, B, O, S	(Studio Tecnico Vettori, 2006)
14	ITA	Multi-family	1960	A, B	(Evangelisti, et al., 2015)
15	ITA	Detached	1950s	A, B, J, K, L, M	(Miceli, 2009)
16	ITA	Detached	1960s	A, B, G, H, K, L, N, R	(Rossetto, 2010)
17	SE	Multi-family	1955	A, B, G, H	(Levin, et al., 2011)
18	ITA	Detached	1960	A, K, L, M	(Casaretto, 2013)
19	GER	Detached	1959	A, B, G, H, K, M, Q	(EuroPHit, 2014)
20	UK	Multi-family	1968	A, B, G, H, N, Q	(EuroPHit , 2014)
21	SPA	Multi-family	1968	A, B, G, H, M	(Passivhaus-Datenbank, 2015)
22	FRA	Multi-family	1956	A, B, G, H, K, L, M, P	(EuroPHit, 2014)
23	NL	Multi-family	1959	A, B, E, G, H, K, L, M, S, T	(LEHR, 2009)
24	GER	Multi-family	1968	A, B, E, F, G, H, I, K, Q, S,	(LEHR, 2009)
25	SZ	Multi-family	1946	A, B, G, H, J, K, L, Q	(IEA, 2011)
26	SZ	Multi-family	1954	A, B F, G, J, K, L	
27	NL	Terrace house	1965	A, B, G, H, K, M, N, A	
28	AU	Multi-family	1952	A, B, C, G, H, K, N, Q	
29	GER	Multi-family	1960	A, B,D, E, G, H, K, L, M	(Konstantinous & Knaack, 2011)
30	GER	Multi-family	1960	A, B, E, G, L, O	
31	SLO	Multi-family	1965	A, B, C, E, F, H	(Spegelj, et al., 2016)
32	SE	Multi-family	1973	A, B, E, F, H, L, P, T	(Beem-Up, 2013)
33	NL	Multi-family	1950	A, B, E, F, G, K, L, M	
34	FRA	Multi-family	1959	A, B, E, F, G, M	

35	SE	Multi-Family	1972	A, F, G, O, P	(Magnusson & Löfberg, 2015)
36	SE	Multi-Family	1972	A, B, E, F, G, K, P, Q, T	(Nilsson, et al., 2011)
37	SE	Multi-Family	1973	A, B, E, G, H	
38	SE	Multi-Family	1972	A, B, E, F	
39	SE	Multi-Family	1966	A, B, G, H, K	(Sjödin, 2014)
40	SE	Multi-family	1968	A, G, L, P, T	(Andersson, 2015)
41	SE	Multi-family	1972	A, B, G, H, P, S, T	(Olsson, 2015)
42	UK	Office	1965	A, B, E, G, H, L, P, T	(Duran, et al., 2015)
43	SE	Multi-family	1974	A, B, E, G, H, P, T	(Stockholms stad, 2014)
44	SE	Multi-family	1971	A, B, G, H, K, L, P, T	
45	SE	Multi-family	1972	A, B, G, H, K, L, T	
46	SE	Multi-family	1975	A, B, E, F, G, H, T	

4.3 Why renovation?

One of the most interesting features when analysing the projects is to understand the reasons why the renovation process has been carried out. If the needs of the stakeholders are understood, it is easier to develop renovation strategies and policies that address them, making the whole process more effective and therefore increasing the renovation rate in the building stock.

The following list summarizes the motives behind the renovations that were encountered when analysing the gathered projects. They are not in order of relevance due to frequency, since there is no statistical relevance.

- **The building had to undergo some other kind of works**. This is one of the most common reasons. If some intervention, has to be carried out, why not take the chance to improve the energy performance of the building? It often happens that some renovation measures, which would not be economically feasible if performed alone, become profitable if carried out within the framework of maintenance works that would be performed anyway. Maintenance is needed when there are some structural defects (such as old balconies), material/components degradation (external plastering, roof tiles or screed, etc.) or some systems have reached the end of their lifetime (ventilation, heating, plumbing etc.). Many buildings are in need of such maintenance work, and pairing the implementation of energy efficient measures is a unique chance to improve the energy rating of the building with a significant lower cost. This was found for instance in Project 1, 5, 13, 15, 20, 24.

- **Planned building expansion.** When a change in the building shape or structure is planned, such as creating new volumes, major construction works are needed and thus the energy performance can be improved by considering an energy retrofit. This option is interesting since the higher rents deriving from the bigger apartments can pay for the refurbishment. This was found for instance in Project 26 and 2.

- **Need to improve the indoor comfort.** The decay of the building envelope and of the building systems often create comfort problems for the dwellers, such as condensation, mould growth, cold draughts and an unsatisfactory operating temperature, too cold in winter and too hot in summer. The implementation of energy efficient solutions has not only the aim to reduce the energy consumption of the building, but also to improve the indoor comfort conditions. This was found for instance in Project 23, 28, 7.

- **Desire of the owner to have an environmental friendly house**. This applies especially to detached houses, where a renovation of the building systems is also possible. Living in a certified house is a personal asset for the owner, as well as a personal gratification for actively contributing to the reduction of global emissions. This was found for instance in Project 16.

- **Deep refurbishment is considered more cost-effective than demolition**. When the building is in such poor conditions that a demolition is taken into account, a careful economic/life cycle analysis has to be performed. Deep refurbishment can be the best choice since in a scenario where only the structural part of the building is conserved, a high degree of freedom to implement renovation measures most suitable for the building can be achieved. This was found for instance in Project 5.

- **Demonstration to prove the efficiency of energy refurbishment.** Many buildings undergo energy refurbishment as a way to demonstrate that it is possible to reduce the energy consumption by a certain percentage, or that the process itself is feasible without major hindrances. This was found for instance in Project 17.

- **Energy bills too high and growing**. A building in poor conditions with a leaky, bad-insulated envelope and inefficient heating system has usually a very high energy consumption, which increases as its conditions become worse by the years. The need for an energy retrofit is therefore driven by economic necessity of savings in the heating/electricity expenses. The higher the consumption, the more convenient the refurbishment. This was found for instance in Project 25, 28.

- **Desire to create a pilot case for refurbishment reference**. Some projects are carefully crafted to create a precedent in retrofit that can work as a benchmark to be followed by other stakeholders with similar interests. The project is usually destined to the retrofit of buildings in a certain geographic area, where there is a specific climate, there is a certain building code and tax incentives or reduction. It is usually run by public authorities. This was found for instance in Project 8.

- **Tenants showing interest in energy efficient renovation.** When the tenants are aware of the worsening conditions of their dwellings and of the benefits that an energy retrofit can bring, they may get involved with the owners to define a common renovation strategy. It is very important to have the tenants on one's side when renovating, since the process (depending on the depth of the renovation) could be quite bothersome for them, due to possible temporary relocation. This was found for instance in Project 27

4.4 Insights on renovation experience

Every project can be considered as a unique case due to its particular conditions and background, but the lessons learned and insights obtained can be generalized and applied to several other different projects. A list is made with some considerations about aspects to be aware of when planning a renovation intervention on a building. Having a clear picture of mistakes to avoid and of potential problems to address from the early planning stages can save money and time in the later phases and streamline the whole process.

- **It is challenging to work with a great number of tenants**. This is a challenge especially in huge social housing buildings, where the number of families involved can easily be greater than 50. The renovation process can start only if an agreement is reached with all the tenants involved, so it is necessary to start early with a good education/dissemination program about the project, to prepare the ground for further negotiation. This is stated in Project 21.

- **It is not easy to find affordable financial tools**. The success of the project often depends on finding the necessary financing, which could be very hard especially if there is no big housing association backing the project. It is also difficult in certain countries to apply to a subsidy program, since the procedure is not clear. Project 10 shows how the absence of liquidity prevents people from retrofitting their dwellings.

- **The project should be backed by a good financial solution for the tenants**. The whole renovation process implicates disturbances and annoyances for the tenants, depending on how disruptive the works are. Having a good financial program to make up for the interferences and to keep the rents reasonably priced is recommended. Sometimes the tenants do not believe that the higher rent will be followed by lower energy costs. A good financial solution was found for instance in Project 28.

- **The project should create added value**. When undergoing renovation, the building has the potential to become a completely new one, both aesthetically and functionally. The ''added value'' is the improved comfort conditions, additional living space, achieved energy efficiency or the adaptation of the building to any future need. It is the added value that increases the worth of the building and therefore pays back (or helps to) the investment made for the retrofit. In Project 2 the living space gets a new layout and a new terrace is built. In Project 26 the apartments are enlarged to get higher rents.

- **Communication is the key**. Before starting with the renovation, it is very important to make sure that the tenants agree with the project, so that the works will be accepted more easily. The communication strategy can be through questionnaires about the conditions of the dwelling, interviews, explanatory letters, meetings and workshops on energy consumption commitment. It is a good idea to have a dedicated person to take care of the interaction with tenants. In Project 27 the tenants themselves expressed interest in participating in the renovation process.

- **The interventions should be as least intrusive as possible.** When considering which renovation measure to apply, precedence should be given to those who do not involve a relocation of tenants, if possible. Some non-invasive techniques which act mostly on the integration of building systems in the façade are getting popular but require a more careful planning. Projects with low distress for the tenants: 22, 24, 27.

- **Choice of the most cost-effective renovation measures.** The project has to undergo a careful life cycle cost analysis to identify the most appropriate renovation measures from an economical point of view. Local incentives and tax deductions must also be taken into account, since some kinds of intervention are subsidized. This is stressed for instance in Project 24 and 20.

- **Money, time and skills are necessary for successful planning.** The only way to reach high building standards and perform an outstanding job is to have the experience, the time and the money to put it into practice. This will also result in a better prediction of the actual energy consumption of the building after renovation. The use of prefabricate elements itself does not guarantee the quality necessary, if it is not backed by skilled work and a careful planning phase. Some projects cannot even start since there are no experienced professionals that know what to do. In Project 25, the importance of those elements is stressed as crucial for a good quality job.

- **When adding insulation in warm countries, other measures should be implemented to counter the increased cooling need in summer.** When insulating in cold countries, the more insulation is usually the better: If the building is in a Mediterranean country, on the other hand, more care is required. Some projects have shown that the thicker the insulation, the higher the cooling summer need, therefore it is necessary to use at the same time solar shading and low-gain glazing. This issue was pointed out in Project 14.

4.5 The Swedish market

The main issues and insights described in the previous chapter also apply as well to the Swedish market when it comes to renovation, as the cited studies point out. The most frequent cause that leads to renovation is urgent technical need and end of lifetime for systems/components, followed by high operation costs, high maintenance and energy costs. Elevating the standard and problems with the indoor climate score are the least frequent causes. The most prioritized factor is the economic feasibility, followed closely by energy efficiency (Thuvander, et al., 2015). The role of the project leader is crucial for the success of the project in terms of sustainability: His engagement will determine whether an ambitious plan is set to achieve high energy efficiency or if a traditional renovation is preferred. The project leader and the others deciding are usually alone and do not get help from external experts (Olsson, et al., 2014). Property managers are very reactive on fixing urgent technical problems and user complaints but they are not very proactive about renovation: The planned maintenance plans are in place but there is little or no plans for a long-term renovation strategy (Thuvander, et al., 2012). When renovating, it is usually aimed at the BBR requirements, even though some companies aim at even a better energy performance. The number of measures that can be implemented depends on the financial means of the company: The room for energy efficient measures is usually limited to what remains of the budget after the necessary maintenance interventions (Hastig & Tapper Jansson, 2014).

4.6 Conclusion

In this chapter, some projects were analysed not only to gather a list of the energy efficient renovation measures that are used in Europe, but also to get some insight on the motives that lead to a renovation process and on the barriers that are encountered. Understanding how owners and professionals think when it comes to renovation and listening to their wishes and points of view is fundamental to implement a more effective renovation process, with the final aim of making refurbishment simpler and widespread.

As for the reasons behind refurbishment, buildings are generally renovated if other kind of work has to be performed anyway, such as maintenance or a building expansion. Another reason for intervening is to improve the indoor comfort, which might be not adequate due to poor envelope conditions. The tenants might be the driver behind renovation if they show interest in environmental issues or complain about the bad conditions: Deep renovation is also usually more convenient than demolition. The economic factors are important as well: Usually renovation is done to address high energy bills that become bigger every year. Renovation projects might also become a pilot case to test energy measures or to prove the efficacy of the refurbishment concept. Having an environmentally friendly house is a matter of prestige and commitment for certain owners.

By analysing how the renovation processes occurred, it is possible to get some useful insight on the most common barriers and issues that are usually encountered. Once again, economic issues in form of the lack of affordable financial tools are decisive to make a project start. A good financial solution is needed not only for the owner but also to make the tenants get through the renovation process, both in form of compensation and to keep the rents on an acceptable rise: This is why the project has to create added value, to help pay off for the renovation process. When choosing which measures to implement, it is always the economic calculation that will assess the most cost-effective ones, which should also be as least intrusive as possible to minimize the nuisances to the tenants. The renovation process is especially cumbersome in huge buildings, where many tenants live: It is of the utmost importance to hold a good communication from the early phases, to have a dialogue with the tenants. In short, for a successful project it is necessary to have enough time to do it carefully, good knowledge of the renovation process for good planning and the adequate financial support to complete the project.

5 Renovation objects in Europe – State of the art

In this chapter, the most important renovation solutions that were encountered during the analysis of the projects (Chapter 4) are presented in this State-of-the-art review. Only the energy-related measures are considered due to the relevance with this thesis, which has the aim of developing solutions packages to effectively renovate a building from the *Miljonprogram*.

5.1 Methodology

The energy efficient solutions found in the renovation project analysis, described in the previous chapter, are now analysed to determine their state-of-the-art, intended as the assessment of the current best practice when renovating. Information was searched on the internet, especially on commercial websites, to find the current practice rather than the soon-to-be-implemented cutting edge solutions that are still in the testing phase or are hard to find on the market due to their novelty.

For every solution, a brief description is provided, as well as the state of the art, to illustrate what is the current best practice and the near future improvements. Untested technologies or those that are still in an early development phase were not considered: The renovation solutions must be ready to implement in a realistic refurbishment scenario. It was also noted in the previous chapter that there is a certain diffidence in using very innovative technologies when renovating due to the degree of uncertainty about their performance, maintenance and effectiveness. The pros and cons are then briefly listed to identify at a glance the strengths and weaknesses of the various solutions: There is no one-size-fits-all renovation measure that can be implemented in every case, but it is rather the building conditions and the desired level of improvement that calls for a specific solution.

The renovation solutions are then analysed according to different indicators, which are of interest for the renovation process; Too often, when considering the refurbishment from a theoretical point of view, only the energy performance is taken into account without checking its feasibility in real life. The parameters considered are therefore advantages and disadvantages, the impact on tenants (whether they need to relocate or if the implementation of the solutions will change their lifestyle) and the climate that suits their application.

To compile the tables, a classification similar to the one displayed in the framework of the NeZeR Project (Promotion of smart and integrated NZEB renovation measures in the European renovation market) was used (TECNALIA, 2014).

5.2 Classification of solutions

<table>
<tr><th colspan="2">External insulation</th></tr>
<tr><th colspan="2">Description</th></tr>
<tr><td colspan="2">Externally insulating a building means that one or more layers of insulation are applied to the external surface. The extent to which the existing surface is demolished depends on its state of conservation and on which kind of insulation is applied. Sometimes a complete removal of the rendering/external covering up to the masonry is done, while in other cases the new layers are just applied on the existing surface. The insulation material is usually in form of rigid panels with different thicknesses, or softer. There are several kinds of insulation materials, but the common feature is that the insulating material has to be anchored to the masonry by means of an adhesive or mechanical joints (or both), then another layer to provide reinforcement is needed, and finally the external render for weather protection can be applied. (Schiavoni, et al., 2016)</td></tr>
<tr><th colspan="2">State of the art</th></tr>
<tr><td colspan="2">The most used insulation materials are EPS (extruded polystyrene foam), XPS (expanded polystyrene foam), which come in rigid panels, mineral wool and organic materials such as cork and cellulose: All those have been on the market for a long time which means that the product is well established. Innovation in external insulation is both in form of materials, with vacuum insulated panels and phase change materials, and prefabricated panels: The latter are just added to the existing surface and therefore must be customized to the building that has to be renovated. (TheGreenAge, 2016)</td></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>✓ Possibility of giving the building a facelift, making it looking better
✓ Enhanced weather protection, noise reduction and wall moisture conditions
✓ Possibility of fixing thermal bridges and air tightness
✓ Prefabricated options
✓ Increase the thermal quality of the building envelope (Everwarm, 2014)</td><td>✓ Not possible if building is listed or in a conservation area
✓ Volume of the building is increased
✓ Need extra fixing at the top if there is not enough roof overhang
✓ Increases the cooling need in warm climates (Everwarm, 2014)</td></tr>
<tr><th>Impact on tenants</th><th>Climate</th></tr>
<tr><td>The only nuisance is due to the scaffolding necessary for the installation and to the noise due to the work process. Since the process concerns the external surface of the wall, the tenants can live in their apartment during the works.</td><td>Suitable for all climates but with different thicknesses. When installing external insulation in warm climates, the cooling need increases since the insulation slows down the night cooling of the building, trapping heat inside: Other measures such as night ventilation and solar shading should be improved to mitigate the negative effects.</td></tr>
</table>

<table>
<tr><th colspan="2">Internal insulation</th></tr>
<tr><th colspan="2">Description</th></tr>
<tr><td colspan="2">Internally insulating a building means adding a layer of insulation on the internal side of the external walls. The insulating material comes either in panels or in blanket rolls, and has to be fastened to the wall by means of some kind of mechanical system, making sure that a vapour barrier is also installed in order to prevent dangerous condensation in the external wall, which gets colder due to the added insulation. The process is usually not disruptive, usually some studs or battens are added to the existing surface and the insulation is fastened to those. The reinstallation of plug sockets, windowsills, light switches etc. should be done with particular care to avoid the penetration of the vapour barrier, given the increased sensibility of the wall to moisture: Accurate sealing is needed. (Homebuilding & Renovation, 2016)</td></tr>
<tr><th colspan="2">State of the art</th></tr>
<tr><td colspan="2">There are three common options for internal insulation. The first is rigid panels that are directly plastered to the wall: The most expensive solution but also the most energy-efficient and fastest, since some have pre-attached plasterboard and vapour barrier. Panels are glued to the wall but screws can also be used. The second is wall battening, either over or under the insulation: Fixing the battens directly to the wall helps when the surface is uneven, creating a good substrate for the insulation, which has to be rigid to be screwed to it. The opposite method, on the other hand, ensures no vapour barrier perforation and more ease to hang things on the wall. The third option is to build a stud wall inside the existing one, with a cavity (usually ventilate) between the two to carry away the moisture: This is used for the cases more at risk of condensation. New materials are being researched to reduce the thickness of the material used, usually mineral wool, rigid foam boards or natural ones as cork or wood fibre, along with fastening techniques that give less thermal bridging. (Homebuilding & Renovation, 2016)</td></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>✓ No alteration of the external surface, can be used in listed buildings
✓ Cheaper and faster than external insulation
✓ Easy to install (Everwarm, 2016)</td><td>✓ Loss of internal space
✓ Intensification of thermal bridges
✓ Walls lose their heat storage capacity, inner thermal comfort might get worse
✓ Condensation problems if insulation is not performed accurately (Everwarm, 2016)</td></tr>
<tr><th>Impact on tenants</th><th>Climate</th></tr>
<tr><td>The tenants cannot live in the room/apartment where the insulation is getting installed.</td><td>The colder the climate, the greater the risk of condensation if the vapour barrier has leakages. Suitable for all climates.</td></tr>
</table>

<table>
<tr><td colspan="2">Cavity wall insulation</td></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">If the external wall has a cavity wide enough (at least 50 mm), it can be filled with some insulating material to increase the heat transfer properties of the wall. In case of new buildings the insulating materials, usually panels or boards, are installed directly in the cavity while in case of retrofitting the cavity is filled with loose materials by making holes in the wall. The insulation will block any convection heat transfer that happens inside the cavity due to air movement. It is important to make sure that the insulation is uniform, to avoid the formation of thermal bridges. This solution is not suited in case of walls in bad conditions with moisture problems. (Olympic Construction, 2015)</td></tr>
<tr><td colspan="2">State of the art</td></tr>
<tr><td colspan="2">There are two common ways of insulating a cavity. The first is to use a foam, usually polyurethane, and the second is to blow a fibrous material such as glass wool or cellulose (some interesting solutions are derived from old minced and treated newspapers). Holes are usually drilled in the external side of the wall, and the material is blown inside by means of a special gun. This technology is well-established, and the present materials have already replaced the old ones that gave rise to mould or allergy problems. (USwitch, 2016)</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>✓ Almost no aesthetic impact
✓ Fast installation
✓ No impact for tenants (Olympic Construction, 2015)</td><td>✓ Possible irregular insulation density (no way to check)
✓ Possible creation of thermal bridges
✓ If there are irregularities in the wall, the material can leak on the inside (Olympic Construction, 2015)</td></tr>
<tr><td>Impact on tenants</td><td>Climate</td></tr>
<tr><td>Holes are drilled from the outside, there might be need to drill them from the inside in case of high-rise buildings. (Superglass, 2016)</td><td>Suitable for all climates.</td></tr>
</table>

<table>
<tr><td colspan="2">Roof insulation</td></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">The strategy for insulating roofs depends on whether the roof is sloped or flat. Insulating a roof is of the utmost importance in a building, given the fact that warm air is less dense than cool air and therefore tends to rise up to the ceiling, creating a stratification in the room. If the roof is poorly insulated, the room ceiling will be cold and transfer the heat outside, creating downward draughts and making difficult and expensive to heat the room. This happens in reverse during the warm season. (EcoWho, 2010)</td></tr>
<tr><td colspan="2">State of the art</td></tr>
<tr><td colspan="2">If the roof is sloped, it is usually best to apply external insulation, in form of replacing the existing roof: The covering tiles are removed and insulation is placed above the existing structure (plus a weatherproof membrane), then new tiles or the old ones are placed back. When doing so, the possibility of making the structure ventilated can be considered (called ventilated roof or cold roof). The insulation is in form of rigid panels: A mix of insulation on the external and internal side can be used to attain the desired U-value if there is access from the internal side. If the roof is flat, there are two options. The first is called inverted warm roof and consists of adding a layer of rigid insulation on top of the existing weather membrane, and then some material to protect the insulation. By doing so, the insulation protects both the membrane and the deck, prolonging their lifespan. The second is called warm roof and is the addition of the rigid insulation on top of the timber structure of the roof: The weather membrane is placed on top of the insulation. This roof, in contrast to the cold roof, is not ventilated. To do so it is necessary to remove the roof covering so it is advised when it should be removed anyway. (Energyquarter, 2015)</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>✓ External interventions, minimum impact on tenants
✓ Can either improve the aesthetics of the building or not alter its appearance. Adding a roof structure makes the roof gain volume though
✓ High energy savings (TECNALIA, 2014)</td><td>✓ Load is added to the structure
✓ Original roof might be removed
✓ Need to fix the accommodation for vents, skylights etc. (flat roof)
✓ Scaffolding needed (pitched roof) (TECNALIA, 2014)</td></tr>
<tr><td>Impact on tenants</td><td>Climate</td></tr>
<tr><td>Minimal.</td><td>Suitable for all climates.</td></tr>
</table>

<table>
<tr><td colspan="2">Attic insulation</td></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">There are two types of attic: Cold and warm. The former means that insulation is placed on the attic floor, keeping the loft cold, while the latter implies insulating immediately below the roof, which keeps the loft warm. (TheGreenAge, 2014)</td></tr>
<tr><td colspan="2">State of the art</td></tr>
<tr><td colspan="2">In cold attics, loose insulation is usually added on the floor, until either it is level with the joists (if there are) and then some rigid panels are added to cover it up, or to a higher level and it is left uncovered. Blanket insulation can also be used; the most common materials are mineral and glass wool. This solution is cheaper than the warm attic and easier to perform, but it leaves the attic more sensible to extreme temperatures in winter and summer. In warm attics, insulation is placed immediately below the roof structure, between the wooden joists. If mineral or glass wool is used, it gets crammed between the joists and then kept in place with wooden battens. Polystyrene slabs can be also used, cut and fitted to the joist space; another option is EPS “squeeze” products that are pre-compressed and expand like springs once they are installed. (USwitch, 2016)</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>✓ With the warm attic, the loft can be inhabited and there is no huge loss of internal space
✓ Very cost-effective measure for energy saving
✓ Cold attic is very easy to insulate
✓ The original roof is untouched (TECNALIA, 2014)</td><td>✓ Condensation risk in the roof
✓ Load is added to the structure
✓ Creation of thermal bridges when insulating
✓ Necessity to relocate cables, lights, vents etc.
✓ A cold attic can experience extreme temperatures in winter and summer (TECNALIA, 2014)</td></tr>
<tr><td>Impact on tenants</td><td>Climate</td></tr>
<tr><td>Minimal but there might some nuisances due to noise and systems relocation.</td><td>Suitable for all climates.</td></tr>
</table>

<table>
<tr><td colspan="2">Low emission windows</td></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">These kind of windows have a specially treated glass surface coating that minimize the amount of infrared and ultraviolet radiation that pass through it, still letting most of the visible light inside the room. Thanks to the low emissivity, the long wave infrared radiation (heat) that is emitted from the room to the outside, is reflected back by the glass coating, improving the window insulation properties. The same happens in reverse during summer, when the low-e coating prevents some of the solar radiation from getting in and transferring heat to the room. In short, the coating helps making the energy stay on the side where it comes from, be it the sun or the heating system in the room. (Glass Eduction Center, 2015)</td></tr>
<tr><td colspan="2">State of the art</td></tr>
<tr><td colspan="2">There are two kinds of coating, according to the production process. The “passive” low-e coating is made mostly with the pyrolytic process, which is very durable: Those windows are especially suited for cold climates since they allow for some solar gains that are useful in winter. The “soft coat” is applied with the Magnetron Sputtering Vapour Deposition (MSVD) process and has better solar control and lower emissivity than the previous coating, and is suited for warm to hot climates. Low-e coatings are very effective in double pane windows. This product is well-assessed now, being used since 1990. The coating can be added to the glass of existing windows. (Glass Eduction Center, 2015)</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>✓ UV radiation is reflected
✓ Solar gains are accepted
✓ Improvement of the window U-value
✓ Existing glass can be coated (Glass Eduction Center, 2015)</td><td>✓ Disturbance to mobile telephone signals
✓ If windows are slightly concave, it might turn them into concentrating mirrors
✓ Possible hazes due to coating (TECNALIA, 2014)</td></tr>
<tr><td>Impact on tenants</td><td>Climate</td></tr>
<tr><td>Minimal.</td><td>Pyrolitic low-e suitable for cold climates, MSVD for warm and hot climates.</td></tr>
</table>

<table>
<tr><td colspan="2">Double glazed windows</td></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">These windows feature two panes separated by an air-filled layer, with a usual thickness of 12-18 cm or a noble gas-filled layer. The fenestration system is airtight. A spacer is in place to separate the panes and seal the gas inside, which due to its very low thermal conductivity acts as an insulant. When talking about the thermal transmittance of windows, it is usually considered the overall window transmittance, which is calculated by taking into account the U-values of glass and frame (Inoutic, 2016). Even though the window has a good air tightness, it is crucial to install it correctly not to create leaks and draughts around the frame that will compromise its performance. Those windows can reach overall thermal transmittance values U_w as low as 1.1 $W/(m^2K)$ (Pilkington, 2015).</td></tr>
<tr><td colspan="2">State of the art</td></tr>
<tr><td colspan="2">This technology as well as low-e, is well established. Continuous progress is made to develop better frames, as now the materials that show the best insulating properties are PVC and wood in combination with the assembly techniques to get the window sealed. Except from air and in newer products, the most common noble gas used in double glazing is argon, due to its low cost; krypton has a lower thermal conductivity but is more expensive and is therefore used only in high performance applications or where the gap between the panes has to be very thin. (Elitfönster, 2010)</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>✓ Improvement of air tightness
✓ Great improvement in U-value compared to single glazing
✓ Possibility to use low emission coatings
✓ Noise reduction (Energy Saving Trust, 2014)</td><td>✓ If the sealing is compromised, the window has to be replaced most times
✓ When retrofitting, the existing window has to be replaced
✓ If replacement is not made correctly, air tightness will be lost (TECNALIA, 2014)</td></tr>
<tr><td>Impact on tenants</td><td>Climate</td></tr>
<tr><td>Minimal.</td><td>Suitable for all climates.</td></tr>
</table>

Triple glazed windows	
Description	
The technology is the same as the double glazing, but with three glass panes and therefore two layer of gas (either air or noble gases). Triple glazing can reach U_w lower than the 0.8 $W/(m^2K)$ limit set by passive house standards are needed, especially in very cold countries. The main benefits are not just in terms of energy consumption but rather of comfort: If the rest of the house is insulated very well but the windows cannot match it, it will end up with cold spots creating draughts and condensation. (Passive House Institute, 2006)	
State of the art	
Improvements are going in the same direction as double glazing, especially better frames and spacers.	
Advantages	**Disadvantages**
✓ The same as for double glazing, presented above plus better U_w values (QualiGlass Windows & Doors , 2016)	✓ The same as for from double glazing presented above ✓ One more pane means slightly less transmitted solar radiation ✓ Heavier than double glazing, up to 50% more (TECNALIA, 2014)
Impact on tenants	**Climate**
Minimal.	Especially in Nordic and central European countries. (QualiGlass Windows & Doors , 2016)

<table>
<tr><td colspan="2">Secondary glazing</td></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">It is the addition of another window to the inside of the existing window, which remains intact in place. This can be done only if there is enough space to install a second window, which can be either fixed and removed during the summer months to provide additional insulation during the colder period, or one that can be opened (hinged, sliding, etc). The aim is to obtain further insulation and sound proofing. (Duration Windows, 2016)</td></tr>
<tr><td colspan="2">State of the art</td></tr>
<tr><td colspan="2">Since this is basically the addition of a window in parallel to the existing one, it is as advanced as the window technology that is to be installed. When mounting the new window, it has to be made with care not to create cold bridges or decrease air tightness. This solution does not alter the external appearance of the window so it is particularly suited for historical buildings. (Duration Windows, 2016)</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>✓ No alteration of external appearance of the building
✓ Improved airtightness
✓ Noise reduction and improved insulation
✓ Makes house safer against intrusion</td><td>✓ Condensation might occur
✓ Less visibility
✓ Cleaning of the existing window becomes more difficult</td></tr>
<tr><td>Impact on tenants</td><td>Climate</td></tr>
<tr><td>Minimal.</td><td>Suitable for all climates.</td></tr>
</table>

<table>
<tr><td colspan="2">External shading</td></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">The concept is to give the building solar protection by limiting the amount of solar radiation that reaches the openings. External shadings can be fixed or mobile, and there are several technologies available according to the surface orientation and latitude. External shading is more efficient than internal shading because the radiation is prevented from reaching the inside of the window, where it heats the internal shading device, which in turn radiates heat to the room. This solution alters the external surface of the building so it cannot be used in conservation areas. (CWCT, 2011)</td></tr>
<tr><td colspan="2">State of the art</td></tr>
<tr><td colspan="2">There are several solutions that have been developed during the years, mostly passive ones. Overhang shelves (either movable or fixed) are placed above the window with the aim of shading in summer when the sun is higher in the sky and letting the precious heat gains of the low winter sun into the room. The overhang depends on the latitude. Side fins are the same concept of the overhangs, but they are placed vertically and their aim is to shade the room from the sun coming from the east or west: A side effect is having the fin that is not shading diffuse daylight into the building. They can be also fixed or adjustable. Window blinds are more efficient than curtains due to their external position. They come in a variety of shapes and materials: External venetian blinds give a good shading and daylight regulation. The improvements in the field of external shading are the mechanization of the systems and connection to an automated control system so that they can have the maximum efficiency all year long. Another interesting technology, especially indicated for sunny climates, that is getting increasingly popular, is the light shelf. It is usually a flat reflective surface, very similar to an overhang that is placed above high level on the external side of an opening to reflect the daylight further into the room, towards the ceiling, reducing the need for artificial lighting. (CWCT, 2011)</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>✓ Reduction of undesired solar gains
✓ Easy to install
✓ Daylight factor and visual comfort increase (TECNALIA, 2014)</td><td>✓ Structural problems with wind- and snow load
✓ Difficult cleaning
✓ Outside view may be considerably reduced
✓ Necessity of proper installation to avoid thermal bridging (TECNALIA, 2014)</td></tr>
<tr><td>Impact on tenants</td><td>Climate</td></tr>
<tr><td>Minimal, it is an external component.</td><td>Suitable for all climates, especially sunny.</td></tr>
</table>

<table>
<tr><td colspan="2">Green roof</td></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">A green roof is the installation of a layer of vegetation on top of the roof: This has several beneficial effects such as providing effective insulation to the roof, retaining, collection and use of storm water, and increasing the air quality. Both roofs help reducing the urban heat island effect. (Green Roof Technology, 2016)</td></tr>
<tr><td colspan="2">State of the art</td></tr>
<tr><td colspan="2">There are mainly two types of green roofs, classified accordingly to the amount and height of vegetation: Extensive and intensive. The former has a thicker layer of earth because it should allow small trees and thickets to grow, while the second consists only of grass and small plants so a thinner earth layer is needed. Extensive roofs can retain more water than intensive roofs, but require a greater maintenance. When installing a green roof, it must be ensured that the underlying structure is well waterproofed and can support the higher load, otherwise the organic layer will damage the roof instead of protecting it against the weather. (Green Roof Technology, 2016)</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>✓ Retention of rainwater
✓ Improvement of air quality
✓ Increased biodiversity
✓ Insulation</td><td>✓ Green roofs need maintenance, especially the extensive
✓ Green roofs add a consistent load to the structure
✓ Might be expensive, the building appearance is altered</td></tr>
<tr><td>Impact of tenants</td><td>Climate</td></tr>
<tr><td>Minimal for cool roofs, tenants might be involved in the maintenance of green roofs.</td><td>Warm climates for cool roofs, all climates for green roof.</td></tr>
</table>

Door replacement	
Description	
Simply replacing the existing external doors with low-U, for the building envelope to get better airtightness.	
State of the art	
To achieve high levels of insulation, doors feature improved core materials such as fiberglass, wood cladding and steel with polyurethane foam core. The frames are also designed to create tighter seals to reduce leakages. (Energy Star, 2016)	
Advantages	**Disadvantages**
✓ Improved insulation ✓ Usually safer than old doors	✓ The cost, it might be expensive
Impact on tenants	**Climate**
Minimal.	Suitable for all climates.

Elimination / Reduction of thermal bridges	
Description	
The better a house is insulated, the greater the percentage of heat loss through thermal bridges. When installing insulation or other components, special care should be taken to avoid the creation or accentuation of thermal bridges, which could compromise the performance of the energy efficient solution. (Low Carbon Housing, 2016)	
State of the art	
The best way to spot thermal bridges is to use a thermographic camera. The building is viewed from the outside through the camera lenses; any localized temperature difference will reveal a thermal bridge in the envelope. They can be geometrical, as a result of the shape of the thermal envelope, such as at the corner of an external wall, repeating (following a regular pattern) or non-repeating (due to discontinuities, they do not show patterns). Fixing thermal bridges that are the result of the construction process, such as those created by balconies, is a hard task and requires major structural interventions, so it should be considered only when other major works are planned. It is easier to fix minor bridges that occur at windows and door frames, vents outlets etc. (Low Carbon Housing, 2016)	
Advantages	**Disadvantages**
✓ Improved comfort conditions ✓ Reduced draughts and condensation (Low Carbon Housing, 2016)	✓ Hard to fix bridging that resulted from a wrong design (absence of thermal breaks) (Low Carbon Housing, 2016)
Impact on tenants	**Climate**
Depending on the intervention, from minimal to huge.	Suitable for all climates.

<table>
<tr><th colspan="2">Air tightness improvement</th></tr>
<tr><th colspan="2">Description</th></tr>
<tr><td colspan="2">It is useless to retrofit a house with a state-of-the-art thermal insulation, if the air tightness (and the ventilation system) is not improved as well. Leakages will make the heated/cooled air flow through the envelope, losing energy used to condition it. Improving the airtightness of a building means fixing the leakages resulting from design mistakes, poor installation of components or degradation of envelope materials. The typical spots where leakages occur are at junctions, which can be between walls and floors (or other walls), opening frames and walls or at the intersection of a component, such as a duct, with the envelope. (Passipedia, 2015)</td></tr>
<tr><th colspan="2">State of the art</th></tr>
<tr><td colspan="2">To check the air tightness level of the building, the blower door test is performed; this method is used mostly for buildings with high performance targets, as passive house. An anemometer can be used as well to identify the specific spots where the leakages occur. If the building does not have an airtight membrane or if it is old and in poor conditions, a new one is installed: The idea is to have an uninterrupted airtight membrane along the building envelope. Special sealing tape is used to fix membrane junctions and intersections with service penetrations and openings. (Passipedia, 2015)</td></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>✓ Improved performance of ventilation system
✓ Reduced condensation problems
✓ Fewer drafts (ISOCELL, 2016)</td><td>✓ An airtight building requires mechanical ventilation not to compromise the internal air quality (ISOCELL, 2016)</td></tr>
<tr><th>Impact on tenants</th><th>Climate</th></tr>
<tr><td>Tenants cannot live in the room that gets retrofitted.</td><td>Suitable for all climates.</td></tr>
</table>

<table>
<tr><th colspan="2">Mechanical ventilation</th></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">If a building has a good airtightness, the most energy-effective way to provide the necessary air exchanges to maintain a good air quality is through mechanical ventilation. The system consists of air ducts to bring the airflow to the rooms and a fan to provide the necessary pressure difference. (Builing Performance Institute, 2016)</td></tr>
<tr><td colspan="2">State of the art</td></tr>
<tr><td colspan="2">The simplest system consists in exhaust ventilation: Air is drained through exhaust vents, making the building under pressurized. The lower pressure sucks the outside air into the building through intended openings in the building envelope, providing fresh air; this system has the advantage that usually the exhaust vents are already in place in the building (kitchen hoods and toilet vents). Supply ventilation works the opposite way: There is only one fan that supplies air to the different zones, making the building pressurized. The exhaust air will therefore flow towards the outside through the spot extractors in toilets and kitchens. The most complete system, putting together the benefits of the previous ones, is called exhaust-and-supply or simply balanced ventilation. It is more complicated, with two ducting systems and two fans, but provides a better control of the indoor air and greater efficiency. When choosing a mechanical ventilation system, the air terminals (supply and exhaust) must be chosen carefully to guarantee the best air distribution in the rooms, minimize noise and have a small pressure drop. Heating and cooling can be supplied through the ventilation system, in that case the system is called HVAC (Heating, Ventilation and Air Conditioning). Heat recovery can used only in combination with exhaust and supply mechanical ventilation (Builing Performance Institute, 2016)</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>✓ Improvement of air quality due to filtering
✓ Efficient, controlled ventilation
✓ Improvement of internal comfort conditions (Builing Performance Institute, 2016)</td><td>✓ Accurate planning needed
✓ Noise related problems may occur
✓ Active system, runs on electricity
✓ Maintenance needed
✓ Might not be easy to install in an old building (Builing Performance Institute, 2016)</td></tr>
<tr><td>Impact on tenants</td><td>Climate</td></tr>
<tr><td>Moderate, workers need access to the apartments to install the ducts and some minor works might be needed to install the units/connect the ducting to the main unit.</td><td>Suitable for all climates.</td></tr>
</table>

Heat recovery	
Description	
The efficiency of a supply and extract ventilation system can be dramatically increased by using heat recovery. The exhaust air is used to preheat or precool the supply air (depending on the season), decreasing the amount of heating or cooling needed by the HVAC. In order to exchange heat, the two airflows meet in the heat exchanger, a component that adds complexity to the system but guarantees high energy savings. (Popular Mechanics, 2016)	
State of the art	
There are several kinds of heat exchangers applied to mechanical ventilation but they can be grouped in two categories: Regenerative and recuperative. In regenerative heat exchangers, the two fluids exchange heat by coming alternatively in contact with the same surface, where the heat is stored before being transferred to the cold fluid. Rotary heat exchangers are the most common choice due to their high efficiency: The two streams flow in a counterflow pattern through a wheel with the rotating heat exchanger medium, a honeycomb structure with high heat conductivity. Recuperative heat exchangers have the heat exchanging medium interposed between the two fluids, which flow on the opposite sides of the heat transferring surface without coming in contact. They are further subdivided in direct, where the fluids share the heat transfer surface, and indirect, if there is an intermediate circulating liquid that transfers the heat from the fluids, that can be very distant from each other. The technologies in order of decreasing efficiency are: Regenerative, direct recuperative, indirect recuperative. There is always a little carryover in recuperative heat exchangers, which means that some odours and pollutants can be transferred to the supply air. No matter the type of heat exchanger, the extract air should always be filtered to avoid contamination. (Popular Mechanics, 2016)	
Advantages	**Disadvantages**
✓ Very high efficiency can be reached ✓ Can also recover moisture (Lawrence Berkeley National Laboratory, 2016)	✓ Space and maintenance needed of the system, especially with moving parts involved and thermal stress on the heat transferring medium ✓ Some contamination of the supply air by the exhaust may occur (Lawrence Berkeley National Laboratory, 2016)
Impact on tenants	**Climate**
Minimal, the heat exchanger is in the AHU room.	Suitable for all climates, especially those heating dominated.

<table>
<tr><td colspan="2">Night ventilation</td></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">When the outdoor air temperature during the day is so hot that opening the windows or not cooling the outdoor air before it enters the building would raise the indoor temperature, and night temperatures are cool, night ventilation can be used. The principle, also called night flushing, is about taking advantage of the free cooling provided by the night air, to cool the thermal mass of the building for the following day. (Designing Buildings Wiki, 2015)</td></tr>
<tr><td colspan="2">State of the art</td></tr>
<tr><td colspan="2">There are three types of night ventilation: Passive, active and hybrid. Passive means that only natural ventilation is used, driven by air pressure difference which is especially effective in tall buildings who can provide a good stack effect at the end of the day. If the ventilation process is fan driven, then it is called active; when a mix of passive and active systems are used, the system is hybrid. (Designing Buildings Wiki, 2015)</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>✓ Use of free night cooling, reduction in cooling loads
✓ No energy is needed for cooling
✓ Applied well in climate regions with high daily temperature difference (hot days and cool nights) (Designing Buildings Wiki, 2015)</td><td>✓ Best suited for buildings unoccupied at night, but not necessarily
✓ Careful planning of thermal mass positioning and air pathways
✓ Suited only if there is enough thermal difference between day and night (Designing Buildings Wiki, 2015)</td></tr>
<tr><td>Impact on tenants</td><td>Climate</td></tr>
<tr><td>Minimal.</td><td>Warm climates with enough thermal excursion between day and night. (Designing Buildings Wiki, 2015)</td></tr>
</table>

<table>
<tr><td colspan="2">Heat pump</td></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">There are different types of heat pumps, air to air, air to water, water to water, geothermal heat pump. Heat pumps are devices that use external work (electricity) to transfer heat from a cold source to a warm source, in the opposite sense of the spontaneous heat flow driven by temperature difference. A fluid is used as carrier to transfer the heat: It can either undergo a compression and expansion process or just stay in its liquid phase, such as in the geothermal heat pumps. They are very effective, since for every unit of electricity used as input they give out usually at least more than two units of heat. When talking about their performance, the Coefficient Of Performance (COP) is used, which is the ratio between the heat power given by the pump and the electric power absorbed by the pump to work. If the pumps work in the right range of temperatures, very high Coefficient of Performance (COP) can be reached. The other indicator is the Seasonal Performance Factor, which describes how the pump works throughout the whole year, i.e. in a wide range of temperatures, and gives therefore a better picture than the COP values (The Green Age, 2014). Heat pumps can be used either to provide heat or cold, according to the direction of heat transfer. (HPA , 2014)</td></tr>
<tr><td colspan="2">State of the art</td></tr>
<tr><td colspan="2">When considering heat pumps, they are classified according to the heat source they get the heat from. The following list describes the most used in residential applications.
• Air source heat pumps: Those pumps have a compression-expansion cycle where the fluid extracts heat from the outside air and either transfers it to the supply air to warm the building, or to a tank of water (either for DHW or heating). The former type is called air-air, the second one air-water heat pump.
• Exhaust air source heat pumps: The functioning principle is the same as described above but the source is the exhaust air coming out from the building. By doing so, most of the heat contained in the exhaust air is recuperated: Since the airflows are usually limited, an electric resistance helps the pump when the need of heat is greater.
• Geothermal heat pumps: The heat source is the ground, exploiting the fact that the temperature of the ground under 10 m is relatively constant. To extract the heat, boreholes are drilled and the heat exchangers inserted in it (usually water pipes). Such a system has the possibility of being used as thermal storage, with heat being absorbed in winter and pumped in during summer. (HPA , 2014)</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>✓ Cheap green energy, high COPs (especially ground source pumps)
✓ Low maintenance required
✓ Heat pumps are environmental friendly (TECNALIA, 2014)</td><td>✓ Trained personnel needed to design, install and perform maintenance or repairs
✓ Space is needed to install
✓ The air source (plus exhaust) pumps might not be able to supply the required heat during extreme cold weather conditions (ibid.)</td></tr>
<tr><td>Impact on tenants</td><td>Climate</td></tr>
<tr><td>Minimal, it is an external component.</td><td>Suitable for all climates, due to their reversible nature (heating and cooling).</td></tr>
</table>

Solar thermal collectors (ST)	
Description	
The solar radiation heats an absorber surface under which a medium (either a liquid or air) flows and gets warmed up. The fluid is either used directly in the desired application or directed to a heat exchanger (also called storage), where heat is accumulated. A solar thermal collector can have different layouts, but the common feature is the presence of a selective, adsorbing surface that should have the highest absorptance as possible and low emission not to disperse heat, and an insulation system to prevent it from cooling down. There are several applications according to the temperature reached inside the collectors, in the state of the art only those of interest for residential use are described. (Warmec Scandinavia, 2016)	
State of the art	
There are two main types of solar thermal collectors, namely flat plate collectors and vacuum tubes. The flat plate solar collector is a panel with a dark absorbing plate upon insulation for reducing the heat losses, which absorbs solar radiation. Fluid tubes are placed over the absorbing plate were the fluid medium (water, a mixture of water and glycol or air are the most common) converts the radiation into heat and transports it by circulation pumps to the storage tank. The heat in the tank goes through a heat exchanger and then is delivered in the building where it is needed. The covering material can be glass or plastic, one or double and with or without anti-reflex; choice is made upon application. The vacuum tubes (or evacuated tubes) consist of glass tubes which are evacuated, to eliminate the thermal convection losses. It contains a smaller finned copper tube, with a selective surface, in which the heat carrier flows. The tubes are connected to a manifold: When the sun shines and heats the collector, the fluid inside the copper tubes gets hot and vaporizes, rising up to the manifold at the top of the collector. It exchanges heat there with another fluid circulating in the main circuit, with the collector tank as final destination. The hot vapour then condensates and falls back into the bottom of the tubes where it starts the process again. (The Renewable Energy Hub, 2016)	
Advantages	**Disadvantages**
✓ Well established system for most of the European countries for renewable and free green energy ✓ Self-contained energy use ✓ Feed-in into the existing district heating system ✓ Flat plate: Easy, robust, can be integrated in the roof, cost efficient ✓ Vacuum tubes: Easy to replace, fitted for industrial applications, while manly applied for solar cooling (Warmec Scandinavia, 2016)	✓ Flat plate: Large area needed ✓ Vacuum tubes: Expensive, limited lifetime ✓ Surplus of hot water in summer, need careful dimensioning ✓ Not competitive against district heating (Ibid.)
Impact on tenants	**Climate**
Minimal, it is an external component.	All climates

Photovoltaic cells (PV)	
Description	
A photovoltaic cell (PV) is a system that generates electricity from the solar radiation. The PV cell is designed as a thin plate of semiconductors, mostly silicon with p-n doping. When the PV cell is exposed to light, energy is transferred from the photons to the electrons in the p-n transition: the free electrons generate a current when the system is closed on a resistance. The PV cells are placed in arrays and mounted in lager units, the PV panels. The PV system can either be a stand-alone system or a grid connected system. The PV panels generates direct current, therefore the system needs an inverter to convert it to direct current. (Electrotec Energy, 2016)	
State of the art	
The PV cells can be divided into three groups: mono- and multicrystalline, thin-film and new dye-sensitised cells. Monocrystalline has a well-defined regular structure, while in polycrystalline the pattern is random. Film types are also getting on the market now: they are second-generation solar cells made by layers of thin photovoltaic materials on a substrate. Dye-sensitised cells are similar to the film ones and are also called Grätzel cells: they feature semi-transparency and represent the third generation of PV cells, with still limited commercial availability (Wikipedia, 2016). The crystalline PV cells are more expensive than the other ones due to a more complicated production process, but the result is a higher efficiency (a greater fraction of the solar radiation is converted into electricity). The PV panels are usually installed on the roof: a careful planning is needed to decide not only the row configuration and inverter choice but also the panel tilt, which varies according to latitude and weather conditions. PV is a well-established technology, nowadays improvements are made in innovative, low efficiency but cheap and environmental friendly materials. (Electrotec Energy, 2016)	
Advantages	**Disadvantages**
✓ Renewable and free energy ✓ Energy production: It is possible to sell it to the grid ✓ Provide additional protection to the roof or façade (Energy Informative, 2014)	✓ Lower performance at higher temperatures ✓ Require space on the roof or facade ✓ Energy has to be consumed as it is produced, otherwise it has to be sold to the grid or accumulated in batteries ✓ Performance decreases with time, recycling issues (Energy Informative, 2014)
Impact of tenants	**Climate**
Minimal, it is an external component.	Mostly in sunny climates.

<table>
<tr><th colspan="2">Condensation boiler</th></tr>
<tr><th colspan="2">Description</th></tr>
<tr><td colspan="2">During a combustion process in a traditional boiler, the exhaust gases are just expelled from the chimney. By doing so, the heat still contained in the fumes is lost: Condensing boilers make the steam condense, recuperating the latent vaporisation heat of the exhaust fumes. The water is then drained away. (National Energy Foundation, 2016)</td></tr>
<tr><th colspan="2">State of the art</th></tr>
<tr><td colspan="2">The efficiency of traditional boilers is around 70-80%, while condensing boilers are over 90%. The most important feature of such boilers is the heat exchanger, which has to withstand the elevated temperatures of the fumes as well as its acid content: Aluminium alloys and stainless steel are preferred for higher temperatures, while plastics are normally used at lower ones due to cost reasons. Since the fumes have to go through a heat exchanger that is as compact as possible due to costs, a fan is used to facilitate the process. (Green Match, 2016)</td></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>✓ Higher efficiency than a traditional boiler
✓ Space saving, does not need a hot water tank and are available in different sizes
✓ Can be fitted into both new and old systems (Green Match, 2016)</td><td>✓ Corrosion issues
✓ Complex system and expensive maintenance
✓ Freezing in the drainage pipe shuts down the boiler (Green Match, 2016)</td></tr>
<tr><th>Impact of tenants</th><th>Climate</th></tr>
<tr><td>No impact.</td><td>Suited for all climates. Care must be taken for very cold climates since the drainage pipe could freeze. (National Energy Foundation, 2016)</td></tr>
</table>

<table>
<tr><td colspan="2">District heating</td></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">District heating is the distribution of heat that is generated in a centralized location, such a power plant, to far located end users, through a network. It is in form of hot water delivered through underground pipes to the desired locations. It has the advantage of the scale efficiency, since the bigger the plant the higher the efficiency in the process, and also due to the fact that heat at around 100 °C is useless for industrial applications. Heat is often a by-product of power plants or other industrial processes, and recuperating this heat has a great environmental meaning, increasing the overall efficiency of the whole process. District heating stands for heating, space heating and hot water in half of buildings in Sweden. (Svensk Fjärrvärme , 2016)</td></tr>
<tr><td colspan="2">State of the art</td></tr>
<tr><td colspan="2">Hot water is pumped into the building from the central heating plant. The water is transported under high pressure in insulated pipes and has a temperature of between 70-120 ° Celsius. In the heating central of the building, there is a heat exchanger which uses the hot water for heating the tap water and radiators in the house. The cooled water is transported back to the central heating plant, preheated and pushed into the system again. (Svensk Fjärrvärme, 2016)</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>✓ Recuperation of waste or by-process heat
✓ Different type of fuels can be used
✓ Economy of scale and greater efficiency than small boilers (Wikipedia, 2016)</td><td>✓ Less found in districts with low population density and small buildings
✓ Needs long term financial commitment and planning
✓ The longer the distance between the plant and the user, the more the lost energy (Wikipedia, 2016)</td></tr>
<tr><td>Impact on tenants</td><td>Climate</td></tr>
<tr><td>No impact.</td><td>Suitable for all climates, especially heat dominated climates.</td></tr>
</table>

<table>
<tr><td colspan="2">Active Thermal storage</td></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">Active thermal storage is an alternative method to store the primary energy over time. The idea is to store somewhere the produced energy that cannot be directly used and would therefore be wasted: This is a broad concept that applies also to the strategy of producing energy when it is cheaper and retrieving it in a second time when it is more expensive. Thermal storage is both for heating and cooling. Energy can be stored on a daily or seasonal basis: For instance, a form of storage is provided by exposing some internal building surfaces to solar radiation during the day in winter so that they will slowly release their heat at night. (Heier, 2013)</td></tr>
<tr><td colspan="2">State of the art</td></tr>
<tr><td colspan="2">There are different methods to store energy in buildings. The most used is sensible heat storage, like hot water tanks, used especially for DHW: Research is being made to improve the insulation levels of the tank with evacuated super-insulation. The underground can also be used as a thermal storage medium, either with boreholes, aquifer or caverns, the first being preferred: It is a very effective for seasonal storage. Phase change materials (PCM) exploit the high melting latent energy, providing thus a greater energy density than the sensible storage and a more controlled temperature. PCM are being integrated in the building walls to increase their thermal mass, with benefits for both heating and cooling (passive strategy). The last strategy is to store heat by chemical reactions such as adsorption. (International Renewable Energy Agency, 2013)</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>✓ Higher access for primary energy and reduced peak loads
✓ Increase of the thermal mass of the building (PCM)
✓ Intelligent use of resources (Heier, 2013)</td><td>✓ Hard to implement, require advanced knowledge
✓ Some technologies are still not established, such as PCM
✓ Need for materials improvement for PCM, limited knowledge about long-term usage (many charge-discharge cycles) (TECNALIA, 2014)</td></tr>
<tr><td>Impact on tenants</td><td>Climate</td></tr>
<tr><td>When thermal storage is used to increase thermal mass, due to its nature, it affects the indoor climate: The most highlighted problem is complaints of cold mornings and warm evenings.</td><td>There are different types of system for both warm and cold climates, which can provide both heating and cooling to the building. (Heier, 2013)</td></tr>
</table>

<table>
<tr><th colspan="2">Building energy Management system (BEMS)</th></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">A building energy management system (BEMS) is a method to control and manage the energy needs of a building. BEMS is a broad concept, it integrates and coordinates the different building systems with the aim of providing a pleasant indoor climate, safety and economical running of the building, without wasting energy. The heart of the system is a computer and sensors that controls not only the HVAC and lighting systems, but fire and security systems as well. (ClimateTechWiki, 2016)</td></tr>
<tr><td colspan="2">State of the art</td></tr>
<tr><td colspan="2">A BEMS consists in a hardware part, which is the processing unit, the various sensors and actuators (if they are not already integrated in the controlled systems) and a software that continuously registers the inputs from the sensors and decides whether to modify the outputs. The level of complexity can vary greatly according to the desired system: Nowadays remote monitoring is possible, as well as communication between different buildings to further optimize the energy savings. (Jones Mei, 2011)</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>✓ Efficient use of energy
✓ Increased comfort conditions
✓ Increased building security (ClimateTechWiki, 2016)</td><td>✓ Need of specialized personnel to install and do maintenance
✓ High initial cost, a major part is the sensors
✓ BEMS can be implemented only if the installed systems allow to be controlled by it (ClimateTechWiki, 2016)</td></tr>
<tr><td>Impact on tenants</td><td>Climate</td></tr>
<tr><td>No impact during the installation. Tenants must be informed on how a BEMS works in order not to override its measures. (ClimateTechWiki, 2016)</td><td>Suitable for all climates.</td></tr>
</table>

<table>
<tr><td colspan="2">Efficient radiators (With thermostatic valves)</td></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">Once that the heating system is upgraded, it is necessary to adequate the heating emitter system. If the envelope has also been improved, the heating need of the building will be lower, which will in turn require smaller or fewer radiators. The new generation of radiators can support low temperature heating systems due to their efficiency that makes them work with water colder than the traditional temperatures. Electric radiators are also gaining popularity (in the UK for instance) thanks to their great flexibility and possibility to be accurately regulated. The working principle of a water radiator is simple: Hot water flows through the radiator, which works as a heat exchanger, yielding heat to the room by both convection and irradiation. Electric radiators are basically resistances that irradiate heat when current flows through them. Radiators are designed to maximize the heat exchange coefficient (both convective and radiative) between air and the surface, which is obtained by choosing materials with high thermal conductivity and large surfaces. (Lawless, 2015)</td></tr>
<tr><td colspan="2">State of the art</td></tr>
<tr><td colspan="2">The main types of radiators for residential applications are water radiators and electric radiators. The former used to be made in cast iron, a material which is today replaced by aluminium, stainless steel or polypropylene, which are lighter and therefore can be easily transported and installed, plus can be shaped in various forms to benefit the design freedom. All water radiators are nowadays equipped with thermostatic valves, which can also be used for retrofitting old ones. They work mechanically, consisting of a valve head that contains a fluid which expands or contracts as the room temperature becomes warmer or colder; the fluid pushes a pin into the valve body, regulating the hot water flow into the radiator. (TheGreenAge, 2016) Electric radiators can be classified into radiating, convecting or both. The infrared heating is interesting since it makes the room warm in a more uniform way, being the irradiated surfaces warmer than the indoor air, increasing the comfort. (Guida Prodotti, 2016)</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>✓ Electric radiators are slim, light and portable, have high efficiencies and require little maintenance. They allow also for an accurate programming, personalizing the comfort conditions room by room. (Guida Prodotti, 2016)
✓ Water systems are present in almost every house so it is easy to retrofit. Aluminium and stainless steel have fast response. (Termosifoni, 2016)</td><td>✓ Electric radiators are expensive and cannot provide heat for a whole building, and they work better when the envelope is good
✓ Water radiators need maintenance and their placement is limited due to the hot water piping system. Aluminium has a little thermal mass so it does not release much heat after the boiler is turned off. (Termosifoni, 2016)</td></tr>
<tr><td>Impact on tenants</td><td>Climate</td></tr>
<tr><td>No impact.</td><td>Suitable for all climates, especially cold.</td></tr>
</table>

<table>
<tr><th colspan="2">Efficient lighting LED</th></tr>
<tr><th colspan="2">Description</th></tr>
<tr><td colspan="2">This kind of artificial lighting consists of light emitting diodes (LEDs), assembled into lamps. LEDs are far more efficient than fluorescent or halogen lights, providing also a longer lifetime: The luminous efficacy, measured in lumen per Watts, keeps increasing as the technology evolves and has reached more than 200 lm/W in laboratory tests. (U.S Departement of Energy, 2013) The estimated useful life of LEDs is between 35000 and 50000 hours. (U.S Departement of Energy, 2009)</td></tr>
<tr><th colspan="2">State of the art</th></tr>
<tr><td colspan="2">The issue with LEDs is that they emit light in a limited wavelength band, which is characteristic of the energy bandgap of the semiconductor that is used to make the light. There are two main ways to overcome this issue and produce white light with LEDs: Either using three LEDs emitting red, blue and yellow (the primary colours) so that the combined light is seen as white, or to use phosphor in a way similar to the fluorescent lightbulbs, to convert blue or ultraviolet radiation to white light. (AlltOmLED, 2015)</td></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>✓ High luminous efficacy, long lifetime
✓ No warm-up time
✓ Very little waste heat production (AlltOmLED, 2105)</td><td>✓ LEDs are current and temperature sensitive: Problems for outdoor applications
✓ The quality of the light is different according to the Spectrum of the LED. (AlltOmLED, 2105)</td></tr>
<tr><th>Impact on tenants</th><th>Climate</th></tr>
<tr><td>No impact.</td><td>Suitable for all climates.</td></tr>
</table>

<table>
<tr><td colspan="2">Presence/daylight sensors</td></tr>
<tr><td colspan="2">Description</td></tr>
<tr><td colspan="2">Presence and daylight sensors measure respectively whether the room is occupied or if there is enough daylight coming from the outside, and act accordingly on the electric light system.</td></tr>
<tr><td colspan="2">State of the art</td></tr>
<tr><td colspan="2">Presence sensors are just photocells that turn on the lighting as soon as someone walks in the room or area. They have a timer and leave the lights on for that amount of time, if the photocell is not stimulated again: Some sensors detect movement as well, so that as long as there is something moving in the room the lights will be on. The technology used is passive infrared or ultrasonic. Absence sensors have the function of turning off the light as no presence is detected: Lights are turned on by the user as he walks in the room. Choice is made upon user preference. Presence sensors are used for big common areas or high occupancy rates, absence sensors for small common areas or offices, and are independent from the occupancy rate. Daylight sensors have a photosensor that measures the illuminance either on the outside of the building (open loop) or on the inside (closed loop). The room lighting is then controlled accordingly, usually by dimming, to make sure that the target illuminance level is always satisfied. (CP Electronics, 2016)</td></tr>
<tr><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>✓ Very effective lighting control strategy (CP Electronics, 2016)</td><td>✓ Final users tend not to like automatic control of lighting, semi-automatic is preferred (such as absence sensors)
✓ High installation costs
✓ Daylight harvesting needs lights that can be dimmed (Carbon Trust, 2014)</td></tr>
<tr><td>Impact on tenants</td><td>Climate</td></tr>
<tr><td>Tenants might not like the automation of a part of the lighting of the house. Better for common areas such as staircases and halls. (Gentile, et al., 2014)</td><td>Suitable for all climates.</td></tr>
</table>

6 Case study

In this chapter, different renovation packages obtained by combining some of the energy efficient solutions listed in chapter 5 are applied to a reference building to test their energy saving potential, in the framework of three scenarios: minor renovation, upgrade of the building envelope to the BBR 22 recommended values and major renovation.

6.1 Method

In order to assess the impact of the different renovation packages contained in the three scenarios, a reference building is chosen and modelled in VIP-Energy, a software that allows specifically to simulate the energy consumption of a building, along with the calculation of the overall thermal transmittance value of the building according to the BBR 22 standard. The energy efficient measures from the state-of-the-art are combined in packages, in the framework of three scenarios. When choosing the renovation solution, literature refers to as choosing out of a list of renovation solutions applied one by one (Wanga, et al., 2015); the measures are either added to the previous one or they are grouped in different packages in order to increase the energy saving potential (Lohse, et al., 2016). Only the annual specific energy consumption of the building is simulated: the base case (the building in its present conditions) is simulated and compared with the energy consumption of the different scenarios and sub-scenarios to identify which combination of solutions decrease the annual consumption below the BBR threshold or the 50% compared to the base case.

6.1.1 Simulation software

VIP-Energy is a software developed by Strusoft AB. VIP-Energy is optimized for calculating the building's total energy performance by a dynamical structured model. The energy need for the building is calculated for heating and cooling with factors that are measurable or known. VIP-Energy is validated according to IEA-DESTEST, CEM-15265 and ASHRAE-BESTEST (Strusoft AB, 2016).

The program calculates the energy consumption according to BBR. It is subdivided into heating demand and electricity (no cooling is considered in this case): Heating is further split into DHW and zone heating, while electricity is split into electric energy for fans, pumps and other electricity-consuming appliances that ensure the functioning of the building services (such as lighting). The household electricity (used to run the household appliances and lighting) is not taken into account by BBR and therefore is not considered. VIP-Energy also gives the total U-value of the building, calculated according the BBR 22 standard. Only final energy (as defined by BBR in chapter 3.3) is taken into account, but it is possible to turn it into total source energy with conversion factors.

Contrary to most of the other simulation programs, VIP-Energy does not require the drawing of the building geometry in 2D or 3D CAD files: the user just inserts the building geometry in a program extension (as well as the floor area), called VIP-Area, by stating the surface of the various building components, both internal and envelope elements. The components are then imported into the program and their properties are assigned. There is a small database of default envelope elements but it is possible to customize the various components according to the specific case, as well as to import materials that are not present in the material database. The program generates automatically the indoor zones according to the floor area. The user enters the internal gains in terms of Watts per square meter; therefore, the program is not used to perform thermal comfort analysis.

It is possible to define schedules for the occupancy, electricity/DHW use, ventilation and so on. Building systems for heating and cooling can be simulated, and different alternatives can be chosen. The user chooses also how the results should be presented, i.e. in accordance to which standard.

6.1.2 The reference building

The reference building is a typical *lamellhus* (see Chapter 3), built during the later years of the *Miljonprogram* (1969-1972), and is now in need for a major refurbishment. It is located in Lund, southern Sweden, in an area called Eddan where several other identical buildings were erected at the same time. The whole area contains 14 three-storey buildings with basements and green areas. The building contains three stairwells and 27 apartments of various sizes: it is shaped as a long, narrow box (about 61 m x 10 m): the long sides face north and south, with an orientation of 26 degrees to the west. The internal floor height is 2.4 m, and the floor slabs are 230 mm thick. Each floor has a heated floor area A_{temp} of 648 m^2. The plan of the ground floor is shown in Figure 6.1. The other floors are identical.

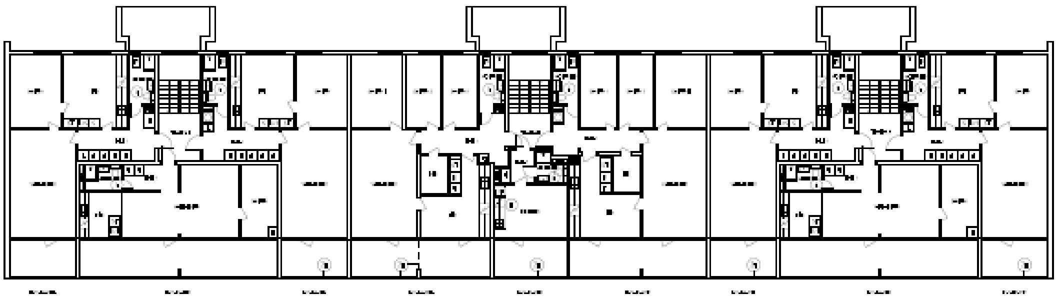

Figure 6.1. Plan view of the ground floor

There is also a basement, whose plan is shown in Figure 6.2.

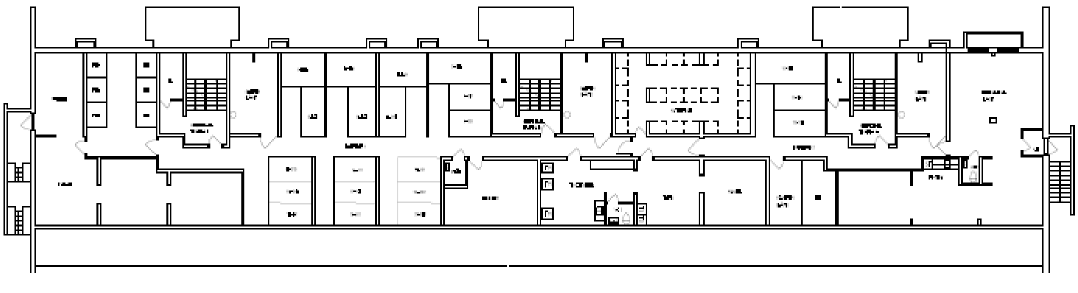

Figure 6.2. Plan view of the basement

6.1.2.1 Input data for the energy simulations

The input data used to simulate the building is shown in Appendix A and B. Some data was assumed, some calculated and some provided by LKF (2016), the housing company which kindly made drawings and energy reports of the building in question available.

6.1.2.2 Building envelope

The windows towards South are still the original ones (with a thermal transmittance of 2.7 W/(m²K)), while on the north side the wooden frame was replaced by aluminium in 2005 which lowered the U-value to 1.7 W/m²K. Some of the balconies have been covered by glazing, as it can be seen in the Figure 6.3 below. The south and north façade have a wooden studs structure, while the east and west façade are made of concrete sandwich walls. Figure 6.3 shows the south side of the building.

Figure 6.3. Reference building south facade with balconies

The load bearing structure is made of concrete. The East and West façade elements have a sandwich structure which consists of 80 mm concrete, 100 mm mineral wool and 100 mm concrete. The loadbearing inner walls are made of concrete and the thickness differs between 150 and 180 mm. The South and North façade have 95 mm insulated wooden studs: The northern façade has 80 mm of concrete on the outer side, while the southern only has 8 mm painted Eternit board. The basement floor and walls are made of concrete and are insulated on the inside. The roof is an unventilated warm roof construction with an 11 degrees inclination and a maximum height of 1.2 m in the middle. It is constructed of wooden rafters with a concrete structure. The balcony floors are concrete prefabricated elements with a thickness of 160 mm, with no thermal separation which means thermal bridging. All the floors are made of concrete and all windows are double-glazed or have additional glazing. Table 6.1 presents the U-values for the building envelope elements, calculated with the software.

Table 6.1. Heat transfer coefficients (U value) for building elements

Elements	**U-Value (W/m² K)**
External wall (South and north)	0.5
External wall (East and West)	0.38
Roof	0.64
Ground floor to the basement	0.85
Double glazed window towards south	2.7
Double glazed window towards north	1.7

The building's ventilation system is an exhaust mechanical ventilation system. An exhaust air fan was installed in 2006 with an efficiency of 70 % at a pressure of 400 Pa. The heat source is district heating.
The airtightness of the building is assumed according to the age of the building and a mean value of three apartments, which have been pressure tested. The air permeability (q50) is estimated to be 0.7 l/(s·m²) at 50 Pa air pressure (Strusoft AB, 2014). For the ventilation, the minimum value recommended by BBR, namely 0.35 l/(s·m²) is used (Boverket, 2015).
The actual hot water use is provided by LKF and is measured 3.4 W/m² for the whole building. The total annual energy use per square meter, referred to the heated floor area A_{temp} in compliance with BBR, is 138 kWh/(m^2A_{Temp}a), including the building's system electricity (for pumps, fans, lighting in common areas etc.).
The input data for the VIP model is presented in appendix A and the drawings of the reference building is presented in appendix B.

6.1.3 Renovation scenarios

The intention is to investigate three scenarios, described in the list below:

- 1) Minor renovation, "business as usual" retrofit: Replacing the components that have reached, or are very close to, the end of their lifetime by new ones that comply with the minimum requirements of the national building code (in this case BBR).
- 2) Renovation of the entire building envelope to achieve the minimum thermal transmittance values stated by BBR. This scenario is different than the previous since the whole building envelope is updated to BBR-class.
- 3) Major renovation/renovation intervention: achieve at least 50% reduction of the base case energy consumption. This is proposed to analyse how far energy savings can be pushed to achieve voluntary building certifications, such as the Swedish *Miljöbyggnad* (SGBC, 2016)

The intention is to apply passive measures (i.e. constructive measures on the envelope) for the first two scenarios, and to implement active measures for the ambitious goals of the last scenario, such as installing a heat recovery system for the ventilation. The heat recovery is also tested in all scenarios to see how it affects the final energy consumption of the building. The *Miljöbyggnad* certification had different criteria, here only the final energy consumption is taken into account: the Gold and Silver levels mean that the final energy consumption of the building is respectively 50% and 75% of the BBR value for that climate zone.

6.1.3.1 Minor renovation scenario

The building has a huge glazed area due to the high number of windows, especially on the southern side: The window-to-wall ratio is about 60%. One of the measures of this package is to change the windows on the South side, from the old double-glazed or two panes to modern windows with U-value lower than 1.3, as the BBR proposes. The windows are old and would need to be changed anyway, since they have reached the end of their lifetime. Those on the North side have an U-value of 1.7 W/(m^{2}K) and are in better conditions, so they are left in place. In addition to that, a simple adjustment of the internal temperature (by adjusting the thermostat) from the present measured 22.8 degrees to 21 degrees will contribute to save energy at no cost. BBR states that the operative room temperature cannot be lower than 18 °C (20 °C in bathrooms) (Boveket, 2015).

Two different types of windows were investigated: Double and triple glazed. The former has an U-value of 1.3 W/(m^2 K) and a total g-value of 77%, while the latter has 1.2 W/(m^2 K) and 68%. Both have been simulated to see how the energy consumption of the building is influenced, and it was decided to present the double glazed in the results since the energy consumption differ little.

As an additional measure, the roof is insulated to achieve the minimum BBR requirements, given its present high thermal transmittance (0.6 W/(m^2 K)). The roof has been insulated externally with 200 mm extruded polystyrene, XPS (as described in the state of the art), to take the chance to renovate the old waterproofing layer. It was also covered with 20 additional mm of weather protection (asphalt). XPS has a very low density (35 kg/m^3) and will not add significant weight to the building structure.

In this scenario it is considered the application of a supply and exhaust mechanical ventilation with heat recovery was also considered, given the high amount of energy loss due to the ventilation. The heat recovery efficiency is supposed to be 85%.

There are four different sub-scenarios:

- “Windows”: substitution of all windows on the southern side with double-glazed ones
- “Windows+roof”: same as before but with an addition of 200mm XPS on the roof
- “Windows+HR”: same as “Windows” but with installation of a supply and exhaust ventilation system with heat recovery with an efficiency of 85%
- “Windows+roof+HR”: same as “Windows+roof” but with installation of a supply and exhaust ventilation system with heat recovery with an efficiency of 85%

6.1.3.2 BBR renovation scenario

In this scenario, the building envelope elements are provided with enough external insulation to reach the minimum thermal transmittance values recommended by BBR (see Chapter 3.4). There are several insulation materials that would be suitable: XPS is chosen again, since it is one the most used insulation materials in such projects. The envelope elements are insulated as shown in Table 6.2.

Table 6.2. Insulation of envelope elements to meet BBR requirements

	XPS thickness (mm)	**U-value according to BBR (W/m^{2}K)**
North wall	120	0.18
South wall	121	0.18
East/West wall	91	0.18
Ground floor	185	0.15
Roof	200	0.13

It was also assumed that the air tightness of the envelope elements improves when adding insulation, reducing from 0.7 to 0.6 l/(s m^2), calculated at 50 Pa pressure difference (q_{50}). The building has also the improvements from the previous scenario (new double glazed windows on both south and north sides and 21 °C set point).

In this scenario, it is also considered the application of a supply and exhaust mechanical ventilation with heat recovery, given the high amount of energy loss due to ventilation. The heat recovery efficiency is supposed to be 85%.

There are two different sub-scenarios:

- “BBR”: insulation of the opaque elements as above, windows as in the minor renovation scenario
- “BBR+HR”: same as above but with installation of a supply and exhaust ventilation system with heat recovery with an efficiency of 85%

6.1.3.3 Major renovation scenario

The intention in this renovation scenario is to reach a 50% reduction in the final energy consumption of the building compared to the base case. A parametric study was performed to see how the energy performance is influenced by different insulation thicknesses and window types. The three considered window types are the double glazed from the first scenario with U = 1.3 W/(m^2 K), and a triple glazed with U = 1 W/(m^2 K) and U = 0.7 W/(m^2 K). For every window type, three insulation thicknesses were taken into account, as shown in Table 6.3. Insulation thicknesses greater than 250 mm were not considered because they provide little benefit, as shown in the next chapter.

Table 6.3. Insulation thicknesses and corresponding U-values for the parametric study

Case/Orientation	Base	Below U=0.15	200 mm XPS	250 mm XPS
	U (W/m^2K)	**XPS (mm)/U (W/m^2K)**	**XPS (mm)/U (W/m^2K)**	**XPS (mm)/U (W/m^2K)**
North/South wall	0.5	160 / 0.149	200 / 0.127	250 / 0.107
East/West wall	0.38	130/ 0.149	200 / 0.114	250 / 0.098
Ground floor	0.85	200 / 0.141	200 / 0.41	250 / 0.117
Roof	0.64	180 / 0.144	200 / 0.131	250 / 0.111

Insulation on the ground floor is added by insulating the basement ceiling. The intention of having all the opaque components with a U-value below 0.15 was taken from the Passive House (Passive House Institute, 2006). Again, the air tightness of the opaque elements is assumed to be 0.6 $l/(s\ m^2)$. It is shown in Chapter 7 that it is not possible to attain a 50% energy reduction only by improving the envelope, so it is also necessary to install the heat recovery on the mechanical ventilation, which becomes then a supply and exhaust system (the original system is just extract ventilation) to support it. The installed heat recovery system is supposed to have an efficiency of 85%. There are two sub-scenarios that are reported in the results:

- "Major": triple-glazed windows with an overall thermal transmittance of 0.7 $W/(m^2\ K)$, insulation of the opaque elements as shown in Table 6.3, "Below U=0.15"
- "Major+HR": same as above but with installation of a supply and exhaust ventilation system with heat recovery with an efficiency of 85%

In regards to the measures to be applied for the major renovation scenario, the parameters considered for the envelope are the insulation thickness (which determines the thermal transmittance) and the thermal transmittance of windows. A parametric study was performed to see how those parameters influence the energy consumption of the building. Three windows were tested: Double glazed with U=1.3 $W/m^2\ K$ and triple glazed with U=1 and U=0.7 $W/m^2\ K$. The total solar transmittance is respectively 77%, 62% and 57%. The analysed insulation levels are as in Table 6.3. The final energy consumption is tested with and without the installation of a supply and exhaust ventilation system with heat recovery with an efficiency of 85%.

6.2 Results

In this paragraph, the results from the simulations of the scenarios are presented. VIP-Energy has the possibility to provide results according to the BBR 22 standard: The final energy consumption is in terms of $kWh/(m^2A_{Temp}a)$.

6.3 Renovation scenarios result

The total final energy consumption of the building in the different sub-scenarios is shown in Figure 6.4.

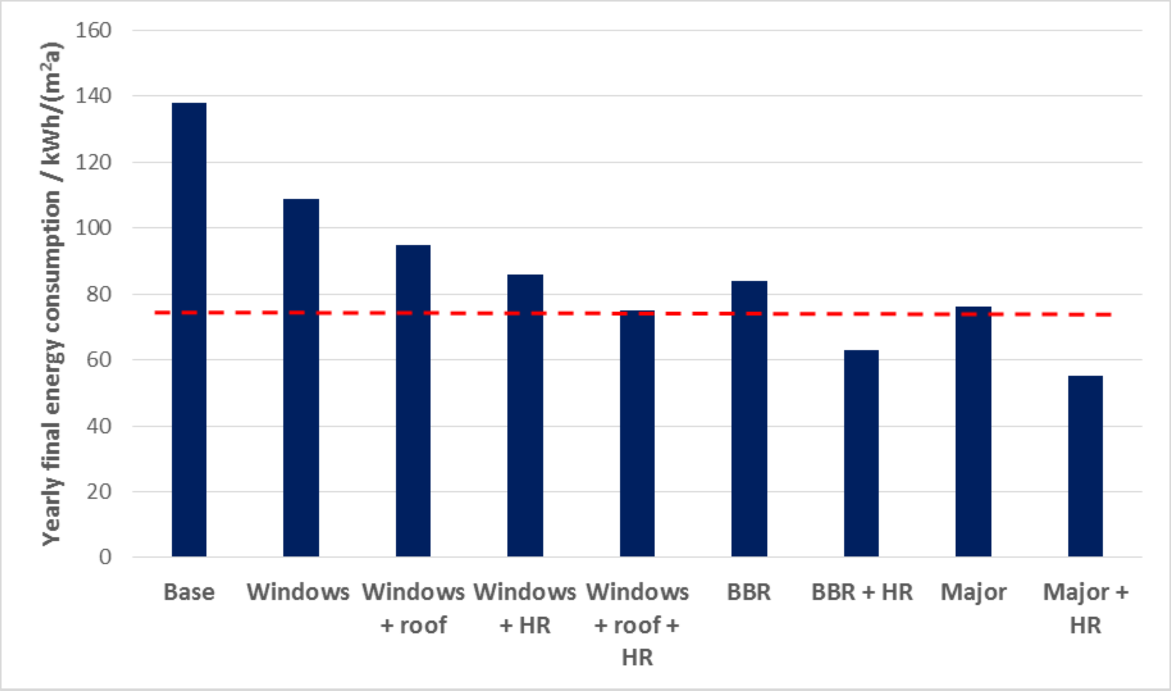

Figure 6.4. Annual final energy consumption for the building in the different scenarios

The dashed line represents the limit set by the BBR 22 for the zone IV, the south of Sweden, which corresponds of a total yearly energy consumption of 75 kWh/($m^2A_{Temp}a$), for non-electrical heated buildings, as shown in chapter 3.4.

Figure 6.5 shows the overall U-value of the building for the different scenarios. Once again, the dashed line is the limit imposed by BBR. Upgrading the envelope components to the threshold thermal transmittance values results in an overall U-value of 0.39 W/(m^2K) right below the 0.4 W/(m^2K) limit.

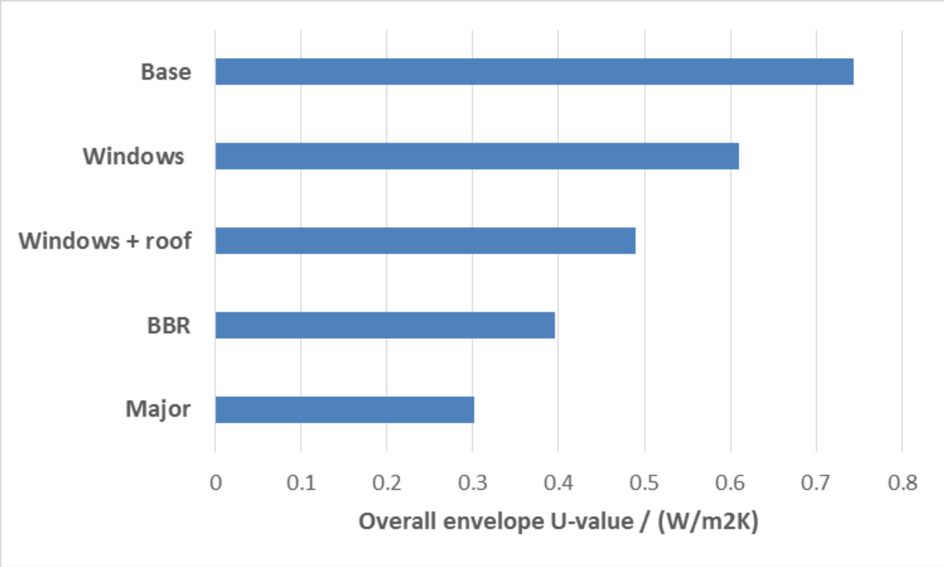

Figure 6.5. Overall envelope U-value for the different scenarios

The energy consumption can be subdivided into heating energy to produce DHW, zone heating and building electricity, Figure 6.6 shows how energy is split in the aforementioned categories. The base case is compared with the ”windows + roof” scenario where the south facing windows are replaced with new double glazed with U=1.3 W/(m^2K) and the roof is insulated according to BBR, then the “BBR” scenario where the envelope complies with the minimum BBR values and finally the “major” scenario, with the opaque elements insulated to reach U < 0.15 W/(m^2 K) and triple glazed, passive house level windows (see chapter 6).

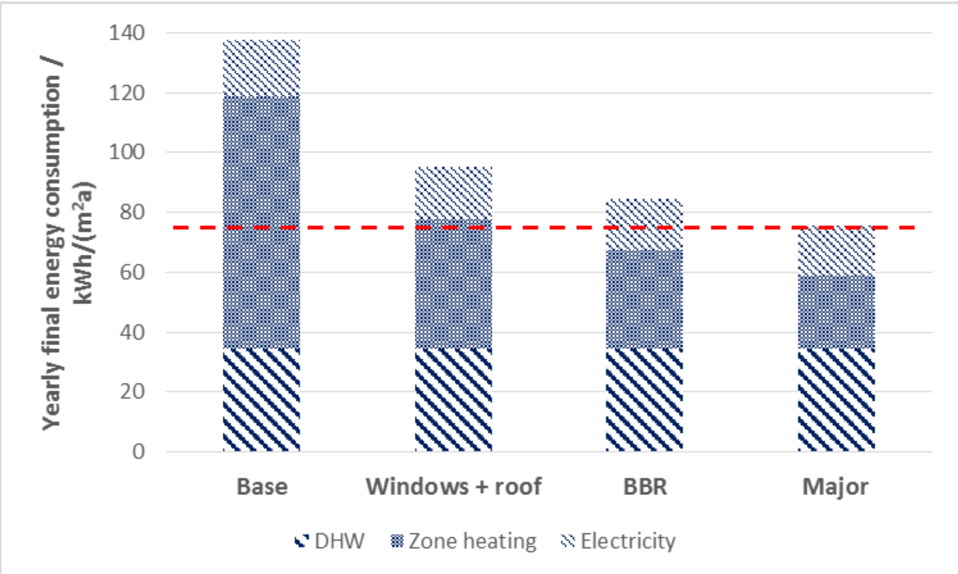

Figure 6.6. Annual energy consumption for the building in the different scenarios, split in electricity, zone heating and DHW

The dashed line is again the limit of an annual consumption of 75 kWh/($m^2A_{Temp}a$): The major renovation scenario is just above this value by 1 kWh/($m^2A_{Temp}a$).

The same scenarios with heat recovery are represented in Figure 6.7.

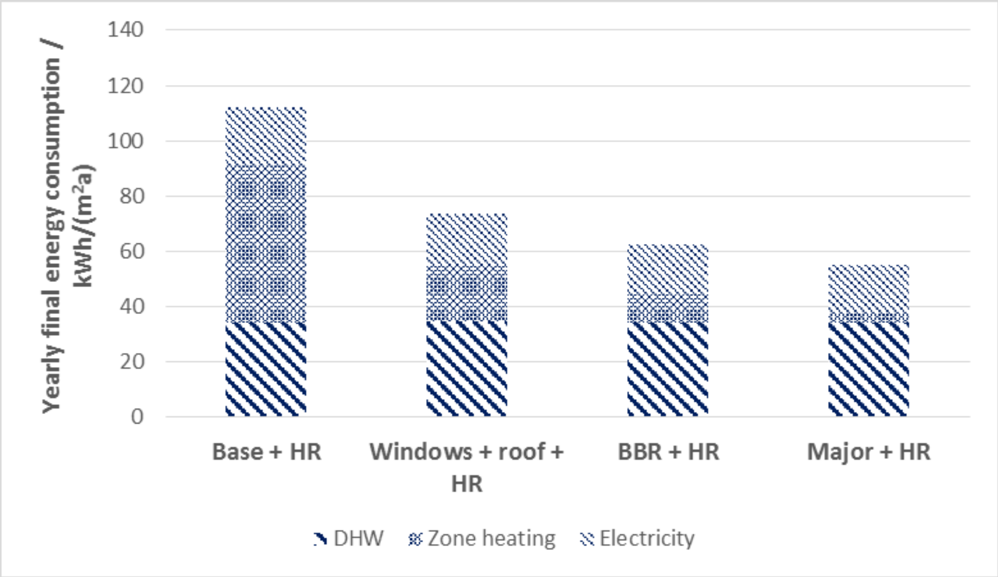

Figure 6.7. Annual energy consumption for the building in the different scenarios with heat recovery on ventilation

The dashed line is still the BBR 75 kWh/($m^2A_{Temp}a$) threshold.

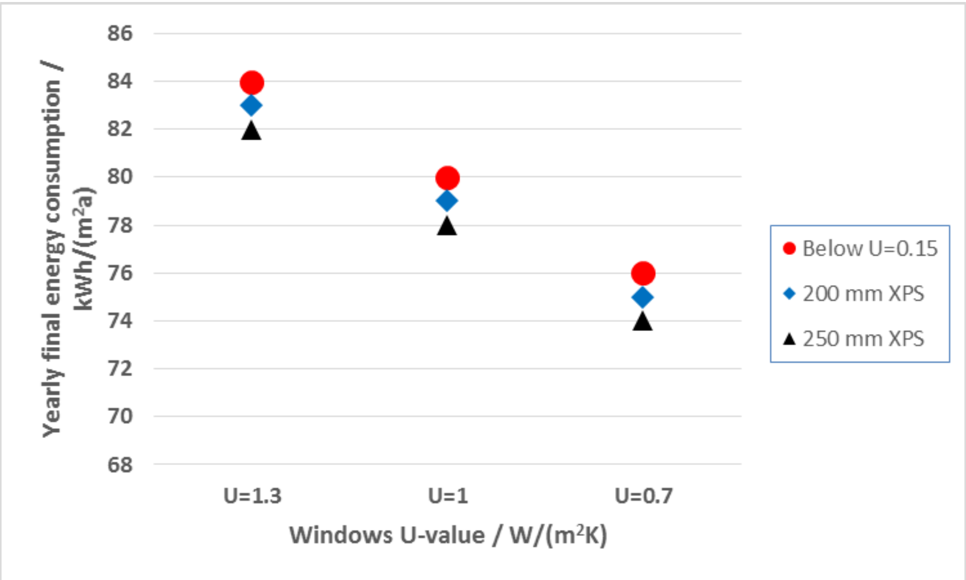

Figure 6.8. Annual final energy consumption of the building for different windows and insulation thicknesses

The different insulation thicknesses make the energy consumption differ, for every window scenario, of just 1 kWh/($m^2A_{Temp}a$). Decreasing the thermal transmittance of the windows by 0.3 W/m^2K results in an energy saving of 4 kWh/($m^2A_{Temp}a$). The same considerations can be made when introducing the heat recovery, as shown in Figure 6.9.

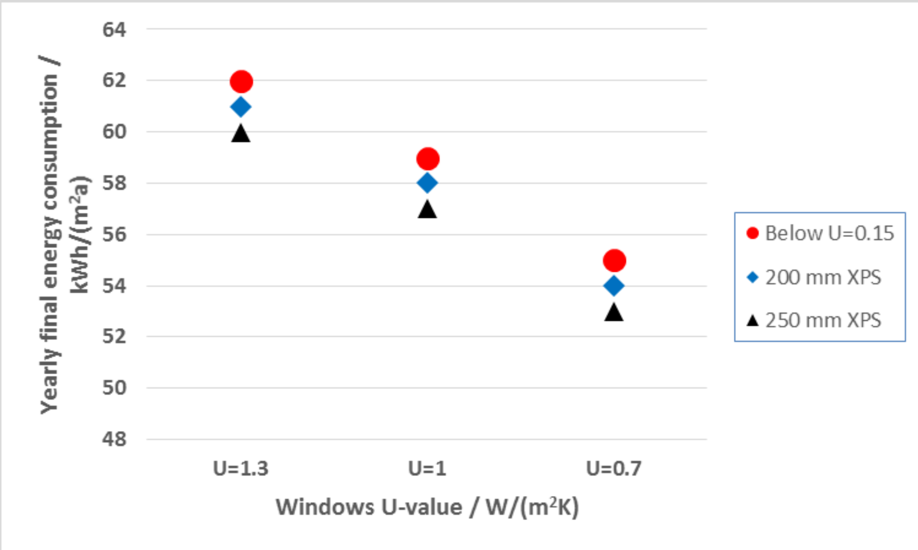

Figure 6.9. Annual final energy consumption of the building for different windows and insulation thicknesses, with heat recovery

The insulation thickness affects the U-value as shown in Figure 6.10. The curves are not linear, which means that the same increase in insulation thickness does not correspond to the same decrease in heat transmittance.

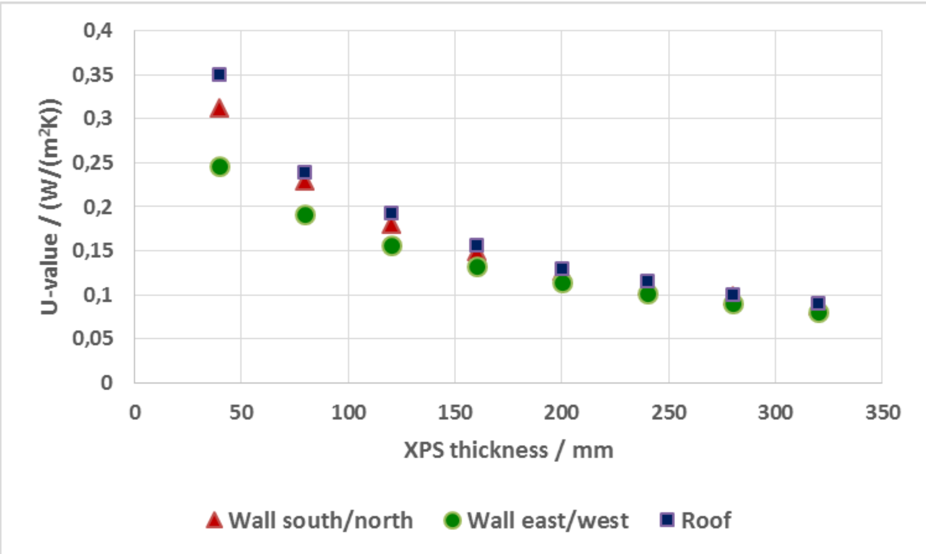

Figure 6.10. U-value as a function of insulation thickness, opaque envelope elements

7 Discussion

Different scenarios were analysed to see how the energy consumption of the building is affected by the proposed renovation solutions.

The scenarios windows+roof+HR and major have about the same annual final energy consumption that satisfies the BBR limit for zone 4 in Sweden. It means that using double glazed windows with an U-value of 1.3 W/(m^2 K) combined with roof insulation and heat recovery on a supply and exhaust ventilation system is equivalent to having all the opaque elements with an U-value just below 0.15 W/(m^2 K) and triple pane windows with U = 0.7 W/(m^2 K) and no heat recovery. Replacing the windows on the South side is the first step to reduce the final energy consumption, due to the present high thermal transmittance and the high window to wall ratio (WWR). Just installing the above mentioned double-glazed windows and installing the heat recovery on the ventilation system makes the final energy consumption decrease 38% .

The building in its present conditions has an overall U-value of 0.74 W/(m^2K): the windows scenario is enough to take it down to 0.61 W/(m^2K), while the BBR scenario is just below the 0.4 W/(m^2K) limit, namely with 0.39 W/(m^2K). The major scenario goes as far as 0.3 W/(m^2K).

In this study it is impossible to reach a 50% reduction in final energy consumption compared to the present one without installing a mechanical ventilation system with heat recovery, as shown in Figure 6.6. By upgrading the envelope in the major scenario, it is only possible to achieve the BBR threshold of 75 kWh/(m^2A_{Temp}a).

The application of a heat exchanger is necessary to reach optimal energy consumption performances. When running the various simulations with heat exchanger, a decrease in the zone heating and a slight increase in fan electricity compared to the sub-scenarios without heat recovery is observed, due to the air pressure loss induced by the heat exchanger. The maximum overall decrease in final energy consumption is 26 kWh/(m^2A_{Temp}a) when applying the heat recovery to the base case (an almost 20% decrease) and the minimum is 20 kWh/(m^2A_{Temp}a) in the windows+roof+HR scenario. It can be therefore inferred that the heat recovery provides at least a saving of 20 kWh/(m^2A_{Temp}a) of total used energy. The installation of heat recovery brings three scenarios under the BBR threshold, of which two (BBR+HR, major+HR) under the 50% mark and one (major+HR) under the 56.25 kWh/(m^2A_{Temp}a) *Miljöbyggnad* Silver requirement concerning energy consumption, with a 60% reduction. From the figures it can be seen how the heating demand for space heating goes down dramatically, making it therefore necessary to evaluate measures for electricity saving and production and also DHW production, such as with solar collectors.

When it comes to insulating the building envelope, a XPS insulation thickness over 200 mm does not bring sensible benefits, since the thermal transmittance of the opaque elements does not decrease linearly with the insulation thickness. For the same window types, with or without heat recovery, the difference in the three insulation thickness cases in terms of final energy consumption of the building is just of 1 kWh/($m^2A_{Temp}a$): it is therefore not worth to exceed the insulation thicknesses described in the “Below U=0.15” case. Between the installation in all the building of windows with an overall U-value of 1.3 W/(m^2K) and 0.7 W/(m^2K) there is a difference in the annual final energy consumption of the building of about 8 kWh/($m^2A_{Temp}a$).

8 Conclusion

The aim of this thesis was to investigate the reasons driving renovation of multi-family post-war buildings in Europe, the barriers and to identify a list of renovation solutions, whose state-of-the-art was presented. The solutions found were applied to the refurbishment of a *lamellhus* in Lund, Sweden, to see whether it is possible to reduce by 50% the energy consumption of a *Miljonprogram* multi-family house by using technologies present on the market

As for the first part, the limited number of projects analysed cannot give the considerations a statistic dimension, but since some of the insights are common to many projects, it can be inferred that they might have a more general value.

The main encountered motivations for renovation are usually the need for the building to undergo some kind of refurbishment when some components reach the end of their lifetime, the indoor climate that does not satisfy the minimum requirements anymore, energy bills keep increasing as the building systems and envelope deteriorate, or a planned building expansion. A study with more projects would be recommended to identify the frequency of these reasons and therefore the most relevant. The present study might have identified the most important ones but a more comprehensive study would also lead to the identification of other reasons.

The most common barriers and issues encountered were: the lack of affordable financial support to realize refurbishments, work processes where a great number of tenants are involved, and the lack of guidelines for integrating the environmental questions from the start of renovation processes. The same considerations as for the reasons for renovating can be made: a more comprehensive study is required to assess the barriers with statistical accuracy. Most of the 46 analysed projects are located in three countries, namely Italy, Sweden and Germany. It would be more accurate to have almost the same number of renovation projects from every European country, but the search for projects was cumbersome.

The state-of-the-art was compiled according to the renovation solutions encountered in the renovation projects: It was decided to include only those contributing directly to the energy consumption reduction of the building, which means that measures such as water saving devices were not considered in the state-of-the-art. Very innovative measures, i.e. still in the research/test phase are not presented in this thesis, since it was intended to apply some of the described solutions to the renovation of a *Miljonprogram* building in a way that could be applied today according to the building codes and local requirements..

The most common barriers and issues encountered are the lack of affordable financial tools to perform the project, working in situations where a great number of tenants is involved, and the lack of guidelines for integrating the environmental questions from the beginning of the renovation process.

As for the second part, it is possible to reach the target of a 50% reduction in energy consumption, according to the performed simulations on a reference building: To do so, the installation of a supply and exhaust ventilation system with heat recovery is crucial. It was demonstrated that it is not possible to reach this goal by just improving the building envelope: Heat recovery in this sense is necessary. When installing it, both the BBR+HR and the major+HR scenarios can reach an energy consumption below both the BBR Zone IV requirement (75 kWh/(m^2A_{Temp}a)) and the 50% one (69 kWh/(m^2A_{Temp}a)), having a total yearly energy use of respectively 63 and 55 kWh/(m^2A_{Temp}a)).

To reach the 50% reduction in energy consumption, it is therefore enough to replace all windows with double glazed ones with a thermal total transmittance of U=1.3 W/(m^2K), install a supply and exhaust ventilation system with heat recovery and insulate the opaque envelope elements to ensure that their U-values do not exceed the ones recommended by BBR. This was achieved by insulating (with external XPS) the north and south facing walls with 120 mm, the east and west walls with 90 mm, roof with 205 mm and the ground floor with 185 mm. It is also possible to reach the *Miljöbyggnad Silver* level concerning energy consumption, (75% of the BBR threshold) by having triple glazed windows with a thermal transmittance of 0.7 W/(m^2K), heat recovery and all the opaque elements with a U-value below 0.15 W/(m^2K). This level of insulation can for instance be reached with additional external XPS insulation: 160 mm on the north/south facing walls, 130 mm on the east/west facing walls, 180 mm on the roof and 200 mm on the ground floor.

Only XPS was analyzed as insulation material, since it was beyond the scope of this thesis to make an accurate assessment of which insulation material would be the best suited for renovation. It was chosen due to its low thermal conductivity and due to the fact that it was frequently encountered in the reviewed renovation projects.

The building has a huge glazed area, with a WWR of almost 40% on the north side and very close to 60% on the south side, which means that the glazing plays a very important role in defining the measures for the energy consumption targets of the building.

Other parameters, such as a life cycle assessment or a life cycle cost analysis, were not taken in consideration since the aim of this thesis is to prove that it is possible to achieve a 50% reduction in the energy use of a building by implementing existing renovation measures. Another aspect that was neglected was the internal comfort conditions: Before renovating, an accurate analysis of the impact of the measures to the indoor comfort has to be assessed to make sure that it becomes better instead of worsening. The building was not equipped with a cooling system, therefore the cooling need was neglected, which has an impact on the indoor comfort. Simulations were performed by using the built-in templates of VIP-Energy concerning the temperature range, which was set to 27 degrees for the Feby template. By simulating with an indoor temperature limit of 27 °C gives in the worst case a cooling need of 1% of the total annual energy consumption of the building, and cooling that occurs in a period of six weeks. If a limit of 25 °C is set, the cooling need becomes 2% in the worst case, with the cooling period spanning through a period of 11 weeks. The more the building gets insulated and airtight, the greater the risk of reaching higher temperatures on the inside.

To reduce the electricity consumption of the building, some measures are recommended but were not investigated in detail and therefore not added in the results section. The pumps present in the building now have a total power of 3050 W. Some of them are old but still in working conditions, so it was decided not to replace them at the moment, also since the common practice encountered in the analysis of the Swedish renovation market is to change components only when their lifetime is ended. Replacing them with more efficient ones would reduce the total power by 600 W, 20% of the original installed power. It should also be considered to replace the current halogen/fluorescent lighting in common areas with LED to further decrease the electricity consumption of the building. A more detailed analysis should be made in this direction.

In this work, the thermal bridging coefficient has not been changed throughout the simulations, since it was supposed that no measures were taken to directly address the issue while renovating, due to its complexity. Thermal bridges, though, are more relevant when the building gets more insulated and airtight, so it is recommended to consider them for further improvements of the energy performance.

It would also be interesting to investigate whether the proposed solution packages could be implemented with success for the other *Miljonprogram* building typologies or other climate zones in Sweden. Further studies should also consider the installation of PV panels to address the electricity demand and solar collectors to produce DHW.

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9.1.1 List of figures

9.1.2 List of tables

10 Appendix

10.1 Appendix A – VIP-Energy input data for references building

The input for the reference building, presented in *Table 10.1*- below, is taken from Information found in VIP-Energy manual or pre-set values in the program, which refers to Feby 12. LKF, who is the owner of the building and provided us with measured values and drawings for the building. Assumptions and measures are made as well according to the drawings, all references are presented in or under each table.

Table 10.1. General inputs for reference building

General		**Reference**
Calculation period - Days	1 – 365	VIP
Horizontal angle to ground	N:20 NE:20 E:40 SE:35 S:40 SW:35 W:40 NW:20°	Assumed
Wind speed as a % of climate file	N:80 NW:80 E:80 SE:80 S:80 SW:80 W:80 NW:80%	Assumed
Sun reflection from ground	20 %	Assumed
Air pressure	1013.21 hPa	VIP
Twist of the building	-26.6°	Measured
Business type	Multi-family building	LKF
Apartments	27 pcs	LKF
Heated floor area	2592.23 m²	Measured
Solid properties, thermal conductivity	1,4 W/m²K	VIP

Table 10.2. Climate data for reference building

Climate data					**Reference**
Malmö 1981-2010	Latitude	55	Degree		VIP
	Highest	Average	Lowest		
Outdoor temperature	28	9	-9,6	°C	
Wind velocity	16	4	0	m/s	
Solar radiation	894	116	0	W/m²	
Relative humidity	100	81	28	%	

Table 10.3. Building elements 1-Dimmensional

Building part types 1-Dimensional - Catalog

Building part name	Material from outside to inside	Layer thickness [m]	Heat conductivity [W/m,K]	Density [kg/m³]	Heat capacity [J/kgK]	U-value [W/m²K]	Permea-bility q50 [l/s,m²]	Solar absorption [%]
South Facade	Eternit	0,008	0,24	1950	840	0,5	0,7	50

	Wooden studs + mineral wool	0,095	0,058	87	961			
	Chipboard	0,015	0,14	600	2300			
	Gypsum	0,013	0,22	900	1100			
North Facade	Concrete	0,08	1,7	2300	800	0,5	0,7	50
	Wooden studs + mineral wool	0,094	0,058	87	961			
	Chipboard	0,014	0,14	600	2300			
	Gypsum	0,013	0,22	900	1100			
Roof	Asfaboard	0,002	0,18	1300	920	0,647	0,7	70
	Cast concrete	0,1	0,14	550	1050			
	Mineral wool	0,105	0,036	50	840			
East & West Facade	Concrete	0,08	1,7	2300	800	0,35	0,7	50
	Cellular plastic Insulation	0,93	0,036	25	1400			
	Concrete	0,08	1,7	2300	800			
Heavy inner wall	Concrete	0,18	1,7	2300	800	3,476	0,1	0
Light inner wall	Gypsum	0,013	0,022	900	1100	0,751	0,1	0
	Wooden studs	0,05	0,045	87	961			
	Gypsum	0,013	0,22	900	1100			
Ground floor	Wood wool plate	0,07	0,075	200	1510	0,855	0,1	0
	Concrete	0,21	1,7	2300	800			
Internal floor	Concrete	0,21	1,7	2300	800	2,628	0,1	0
	Wood wool plate	0,013	0,75	200	1510			
Attic floor	Concrete	0,14	1,7	2300	800	0,279	0,1	0
	Mineral wool	0,12	0,036	50	840			
Basement floor (ground floor)	Draining gravel	0,2	1,4	1800	1000	0,163	0,5	0
	Light concrete	0,14	0,106	400	1050			

Basement walls (south, west, north, east)	Draining gravel	0,3	1,4	1800	1000	0,165	0,5	0
	Light concrete	0,23	0,106	400	1050			
	Insulation Mineral wool	0,07	0,036	50	840			
		Measured	VIP	VIP	VIP	LKF	Assumed	Assumed

Table 10.4. Building elements 2-Dimensional

Building part types 2-Dimensional - Catalog

Build part name	Psi-Value [W/mK]	Width [m]	Permeability q50 [l/s,m²]	Solar absorption [%]
Window stealth	0,127	0,2	0	0
Outside corner	0,2163	0,4	0,5	50
	VIP	Assumed	Assumed	Assumed

Table 10.5. Building elements 3-Dsimensional

Building part type 3-Dimensional - Catalog

Build part name	Chi-Value [W/K]	Area [m²]	Permeability q50 [l/s,m²]	Solar absorption [%]
Balcony	0,459	0,2	0,05	70
	VIP	Assumed	Assumed	Assumed

Table 10.6. Description of the reference building

Building

Build part name	Orientation	Amount, Area [m²], Lenght [m], Number [pcs]	Tilt [degree]	Lowest level [m]	Highest level [m]	U-Value [W/m²K], Psi-Value [W/m,K], Chi-Value [W/K], incl soil delta-U
South facade	South	207,9 m²		0	2,49	0,5 W/m²K
North Facade	North	354,8 m²		0	2,49	0,5 W/m²K
Roof South	South	332 m²	11 degree	2,49	2,49	0,647 W/m²K
Roof North	North	332 m²	11 degree	2,49	2,49	0,647 W/m²K
East Facade	East	86,3 m²		0	2,49	0,35 W/m²K
West Facade	West	86,3 m²		0	2,49	0,35 W/m²K

heavy inner wall	Inner	1240 m²			3,665 W/m²K
Light inner wall	Inner	168,1 m²			0,751 W/m²K
Ground floor	Inner	640,5 m²			0,855 W/m²K
Internal floor	Inner	1281 m²			2,628 W/m²K
Attic floor	Inner	640,5 m²			0,179 W/m²K
Basement floor (ground floor)	BF > 6 m	655 m²	-2,4	0	0,163 W/m²K
Basement walls (south, west, north, east)	BW 0-1 m	144,3 m²	-2,4	0	0,199 W/m²K
Basement walls (south, west, north, east)	BW 1-2 m	144,3 m²	-2,4	0	0,160 W/m²K
Basement walls (south, west, north, east)	BW > 2 m	75 m²	-2,4	0	0,124 W/m²K
Basement walls Heavy inner	Inner	319,2 m²	0	0	3,872 W/m²K
Window stealth South	South	813,3 m	0	0	0,127 W/m,K
Window stealth North	North	430,5 m	0	0	0,127 W/m,K
Outside corner South	South	8,1 m	0	0	0,216 W/m,K
Outside corner North	North	8,1 m	0	0	0,216 W/m,K
Outside corner East	East	8,1 m	0	0	0,216 W/m,K

Outside corner West	West	8,1 m		0	0	0,216 W/m,K
Balcony	South	123 pcs		0	0	0,459 W/K
		Measured	Measured	Measured	Measured	VIP

Table 10.7. Shading device

Sun shading

Designation	Function	Value	Activates at room temperature over
Balcony	Shading upper edge	85,0 // 43,0	0 °C
		Measured	

Table 10.8. Description of building parts

Building part - Window, Door

Description	Orien tation	Area [m²]	Amount of glass [%]	Solar trans mittance [%] Total (g)	Solar trans mittance [%] Direct (ST)	U-value [W/m²K]	q50 leakages [l/s,m²]	Sun shading
Big N Window	North	110,9 m²	70	76	60,8	1,7 W/m²K	0,7	
Small N Window	North	16,2 m²	70	76	60,8	1,7 W/m²K	0,7	
Stair N Window	North	7,6 m²	70	76	60,8	1,7 W/m²K	0,7	
Balcony door Window	South	73,7 m²	70	76	60,8	2,6 W/m²K	0,7	Balcony
Big S Window	South	77,8 m²	70	76	60,8	2,6 W/m²K	0,7	Balcony
Small S Window	South	113,4 m²	70	76	60,8	2,6 W/m²K	0,7	Balcony
Medium S Window	South	14,6 m²	70	76	60,8	2,6 W/m²K	0,7	Balcony
Medium sm S Window	South	10,8 m²	70	76	60,8	2,6 W/m²K	0,7	Balcony
External door	North	8,6 m²	0	0	0	1,5 W/m²K	0,5	
		Measured	Assumed	VIP	VIP	LKF	Assumed	Measured

Table 10.9. Operating data for the reference building

Operating data								
Operating casae name	Activity energy [W/m²]	Activity energy external [W/m²]	Building energy to room [W/m²]	Building energy extern [W/m²]	Hot tap water [W/m²]	Moisture added [mg/s,m²]	Highest room temperature [°C]	Lowest room temperature [°C]
Multi-family buildings 22	5	0,7	1	0,4	3,4	0,8	27	22,8
Basement	0	0	5	0	0	0	27	18
	Assumed	VIP	VIP	VIP	LKF	VIP	VIP	LKF

Table 10.10. Operating scheme

Operating times				**Reference**
Operating case name	Weekdays	Week number	Time	
Multi-family buildings 22	Monday	1-53	00:00-24:00	Assumed
	Tuesday	---	Monday	
	Wednesday	---	Monday	
	Thursday	---	Monday	
	Friday	---	Monday	
	Saturday	---	Monday	
	Sunday	---	Monday	

Table 10.11. Input for ventilation

Ventilation unit					
Unit designation	Supply air fan pressure [Pa]	Supply air efficiency [%]	Exhaust air fan pressure [Pa]	Exhaust air efficiency [%]	Control state
Exhaust air	0	0	400	70	Exhaust air
Airing	0	0	0	0	Airing
			Assumed	Assumed	

Table 10.12. Operating scheme for mechanical ventilation fan

Ventilation units - Operating time, Flow						**References**
Operating designation	Weekdays	Supply air [l/s,m²]	Exhaust air [l/s,m²]	week number	Start time-End time	
Exhaust air						
	Monday	0	0,35	1-53	00:00-24:00	Assumed
	Tuesday	---	Monday			
	Wednesday	---	Monday			
	Thursday	---	Monday			

	Friday	---	Monday			
	Saturday	---	Monday			
	Sunday	---	Monday			
Airing (Building, not basement zone)						
	Monday	0,025	0,025	1-53	00:00-24:00	Assumed
	Tuesday	---	Monday			
	Wednesday	---	Monday			
	Thursday	---	Monday			
	Friday	---	Monday			
	Saturday	---	Monday			
	Sunday	---	Monday			

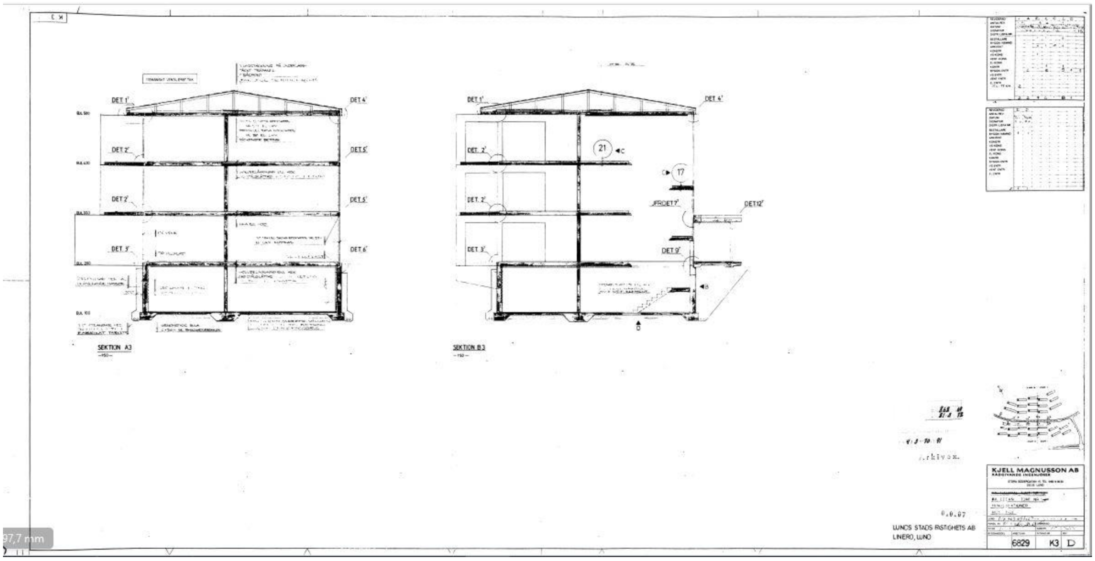
Table 10.13. Heat supply input for the reference building

Heat supply			**Reference**
Heating system	Operating point 1	Operation point 2	
outdoor temperature	-20 °C	20 °C	VIP
Supply pipe temperature	55 °C	20 °C	VIP
Drain pipe temperature	45 °C	20 °C	VIP
Hot tap water (DHW)			
Cold water temperature	8	[°C]	VIP
Hot tap water temperature	65	[°C]	VIP
Internal heat losses	0,285	W/m,K	LKF
Internal pipe length	196	m	Measured from drawings
External heat losses	0,97	W/m,K	LKF
External pipe length	30	m	Measured from drawings

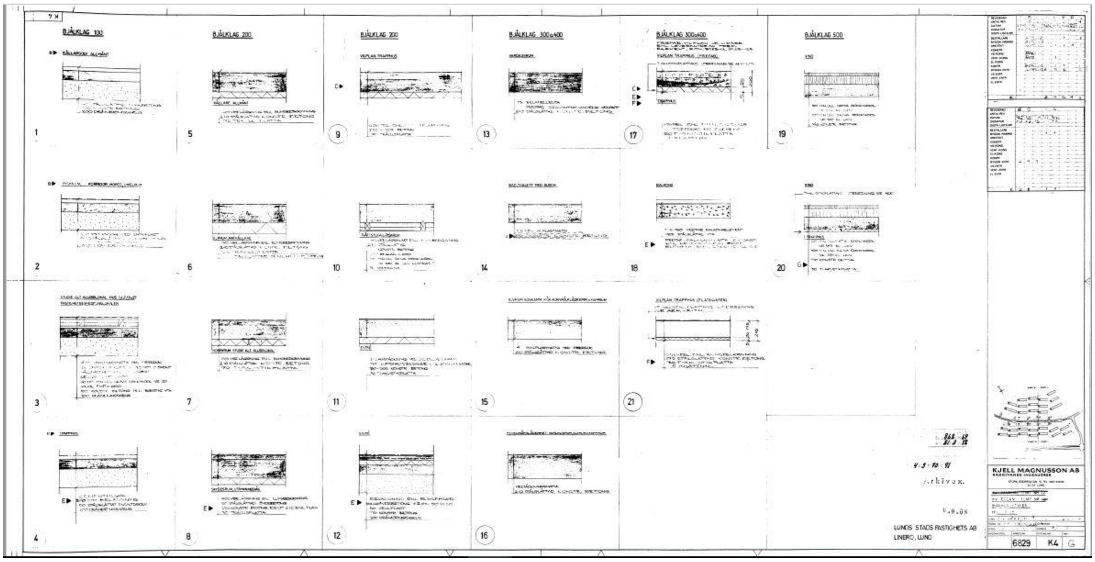
Table 10.14. Other input data for the reference building

Other	**References**
Electricity for circulation pumps 3050 W	LKF
Lowest Dimension outdoor temperature for heating -9,6 °C	VIP
Highest Dimension outdoor temperature for comfort cooling 100 °C	Assumed
Passive cooling	LKF

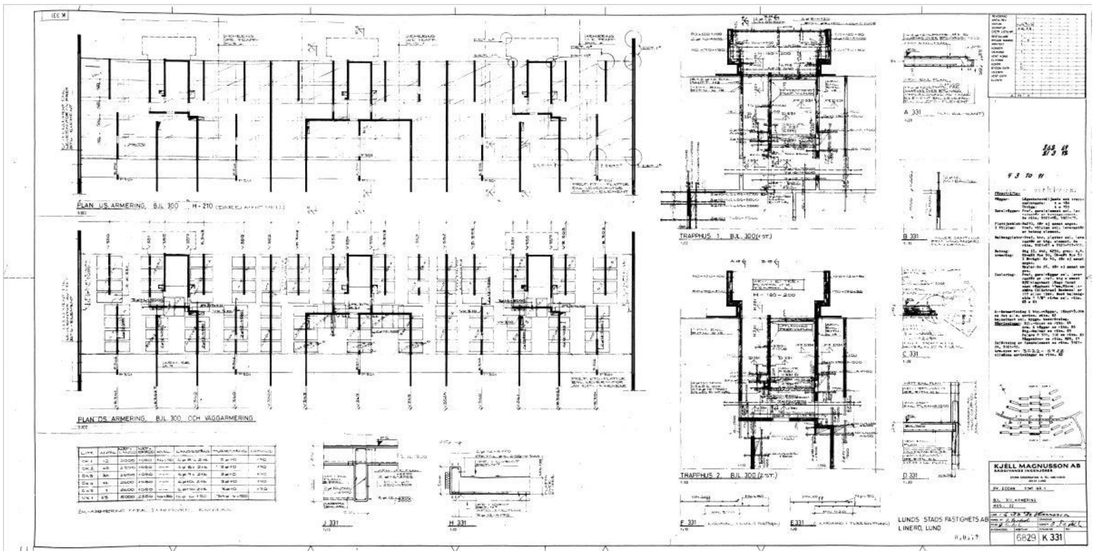
Appendix B1 - Section from East



Appendix B2 – Element structure



Appendix B3 – Inner walls



Summary

About 40 % of the residential European building stoke was built before 1960 and is now in need of renovation; when the buildings were erected, no consideration to energy efficient and sustainability was taken. Since different components of the buildings have reached the end of their lifetime, there will likely be only one complete renovation cycle of the building stock before 2050. This means that there is one chance to do it right or to fail. Since renovation would need to be performed anyway, it is a unique chance to apply some energy efficient retrofit measures as well, which is cheaper than doing it in a separate intervention.

This thesis wants to provide support for the renovation of multi-family buildings of the *Miljonprogram* era, by advising in the renovation process through suggesting several packages of retrofit solutions that could suit different stakeholders' requests.

The Swedish building stock is in line with the European one (as distribution of single- vs multi-family houses). The buildings erected in Sweden in the period 1950-1970 represent 22.6% of the single-family and 41.5% of the multi-family stock. Data for Europe shows that more than half of the buildings were built before 1970: The number of aging buildings is high and the potential for energy saving through major renovation remarkable.

Whenever a building is being erected or renovated, there are sets of rules that must be followed concerning both which materials and components to use and the construction process itself. Building codes are made of different parts: The requirements on energy efficiency can be a chapter in the building code, usually giving concise instructions and referring to the specific standard, which is more comprehensive and detailed. It depends from country to country how much information from the standard, as well as methods to calculate a certain value, are included in the building code. This work will follow the recommendations prescribed by the BBR 22, the Swedish building code.

In order to understand which renovations measures are applied as best practice in current projects, a research was performed on completed or ongoing projects in Europe concerning the renovation of multi-family post-war buildings. For every project, the energy efficient retrofit measures was listed. table. This does not suppose any statistical relevance, due to the small number of cases considered, but rather to help identify a list of possible solutions and define the state-of-the-art.

One of the most interesting features when analysing the projects is to understand the reasons why the renovation process has been carried out. If the needs of the stakeholders are understood, it is easier to develop renovation strategies and policies that address them, making the whole process more effective and therefore increasing the renovation rate in the building stock. Motives behind the renovations were encountered when analysing the Project.

- The building had to undergo some other kind of works anyway
- Planned building expansion
- Need to improve the indoor comfort

- Demonstration to prove the energy efficient refurbishment, and get lower energy bills
- Desire of the owner and or tenants, to have an environmental friendly house

The most prioritized factor is the economic feasibility, followed closely by energy efficiency. When renovating, it is usually aimed at the BBR 22 requirements, even though some companies aim at even a better energy performance. The number of measures that can be implemented depends on the financial means of the company: The room for energy efficient measures is usually limited to what remains of the budget after the necessary maintenance interventions. Renovation projects might also become a pilot case to test energy measures or to prove the efficacy of the refurbishment concept. Having an environmentally friendly house is a matter of prestige and commitment for certain owners.

The most important renovation solutions that were encountered during the analysis of the projects has been listed, described and analysed according to different indicators which are of interest for the renovation process. The indicators are; advantages, disadvantages, impact of tenants and in which climate the application is suitable. Only the energy-related measures are considered due to the relevance with this thesis, which has the aim of developing solutions packages to effectively renovate a building from the *Miljonprogram.*

According to the renovation solutions, three different scenarios were simulated, to investigatre their impact on the energy consumption reduction of the reference building.

- Minor renovation, “business as usual” retrofit: Replacing the components that have reached or are very close to the end of their lifetime with new ones that comply with the minimum requirements of the national building code
- Renovation of the building envelope to achieve the minimum thermal transmittance values stated by BBR
- Major renovation, intervention to achieve a 50% reduction of the baseline energy consumption, “Dream renovation”, to see how far the energy savings can be pushed to reach some certifications such as *Miljöbyggnad*

The reference building is a typical *lamellhus* in Lund, built 1969-1972, and the used software is VIP-Energy. The building has a huge glazed area due to the high number of windows, especially on the southern side: The window-to-wall ratio is about 60%.

The first one of the measures of the packages will be to change the windows on the south side, from the old double-glazed or two panes ones to modern windows with U-value lower than 1.3, as the BBR prescribes. The windows are old and would need to be changed anyway. As an additional measure, for every scenario the roof has been insulated to reach the minimum BBR requirements, given its present high thermal transmittance. For the second renovation scenario the building envelope elements are provided with additional external insulation, to avoid moisture risks: There are several insulation materials that would be suited for the task, it was decided to use XPS since it was the most used in the projects. It was also supposed that the air tightness of the envelope elements improves when insulating, going down to 0.6 l/(s m^2), calculated at 50 Pa pressure difference (q_{50}). According to the major renovation scenario, to reduce 50 % in energy consumption a parametric study was performed to see how the energy performance is influenced by different insulation thicknesses and window types. It is shown that it is not possible to attain a 50% energy reduction only by acting on the envelope, but it is also necessary to install the heat recovery on the mechanical ventilation, which becomes then a supply and exhaust system. The dream scenario is therefore the previous with the installation of heat recovery on a supply and extract mechanical ventilation system to see how far low it is possible to go in the energy savings.

Both the BBR and Dream scenarios are well below the BBR requirements, and the Dream one also fulfils the *Miljöbyggnad* Silver requirement concerning energy consumption, it being only 55 kWh/m^2.

The application of a heat exchanger is necessary to reach high performances. When running the various simulations with and without heat exchanger, it was observed a decrease in the zone heating and a slight increase in fan electricity due to the pressure loss introduced by the heat exchanger. The maximum overall decrease was 26 kWh/m^2 when applying the heat recovery to the base case and the minimum was 20 kWh/m^2 in the south windows scenario with roof insulation. It can be therefore inferred that the heat recovery provides at least a saving of 20 kWh/m^2 of total used energy.

Different scenarios were tested to see how the energy consumption of the building was affected by the combination of renovation solutions. Other parameters, such as a life cycle assessment or a life cycle cost analysis, were not taken in consideration since the aim of this thesis is to prove that it is possible to achieve a 50% reduction in the energy use of a building by implementing existing renovation measures, with no regards to issues such as thermal comfort.

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