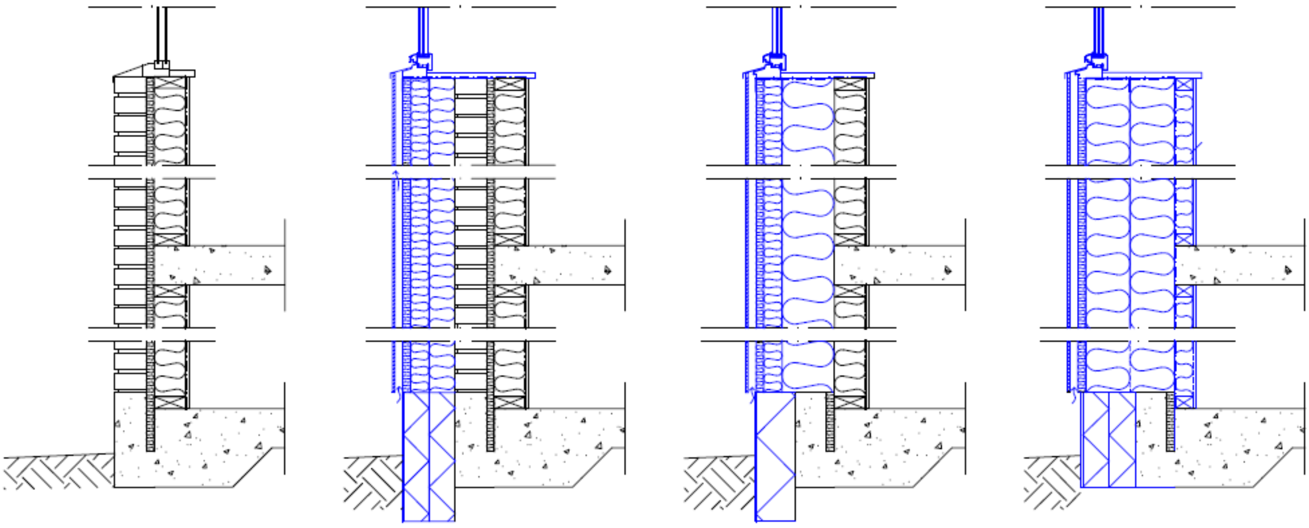

Evaluation of Energy Improving Exterior Wall Renovation Measures for Multi-family Houses Built 1961-1975

Master of Science Thesis in the Master's Programme Structural Engineering and Building Performance Design

MIKAEL ERIKSSON ANDIN

Department of Civil and Environmental Engineering
Division of Building Technology
Building Physics
CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

Renovation solutions for exterior walls that improve the energy consumption were studied for a common multi-family house built during 1961-75. The wall solutions involve additional insulation with mineral wool and new façade panel, air tightening and upgrade of windows. They were evaluated in terms of energy efficiency, moisture safety, indoor comfort and cost. The results can be used as a basis for a methodology for evaluation of different renovation options.

Houses built during the record years (1969-75) need extensive renovation, which gives an opportunity to perform cost efficient energy improving measures. The Swedish parliament has set high goals for future energy consumption in the building sector. A good renovation solution was defined as energy- and cost efficient, moisture safe and allowing a good indoor climate.

The studied renovation options were compared by theoretically applying them on a real building. Energy consumption was assessed by transient calculations performed by the computer software IDA. The size of thermal bridges was needed as input and they were calculated numerically under steady state conditions with the software Heat2. The heat and moisture condition in the wall was assessed with the numerical software WUFI 1D. Cost efficiency was evaluated by a life cycle cost analysis. Assessment of indoor thermal comfort was based on operative temperatures, floor temperatures, and radiant thermal asymmetry.

In order to reach the desired energy goals; to decrease the energy consumption by half, renovation is needed for several building parts and the consequence is difficulties to reach cost efficiency. However, the choice of input data such as energy price and energy price increase is crucial for the results i.e. a small change affects the outcome significantly. Reduction of energy consumption with 50% can be achieved to a lower cost than for the real renovation of the studied building. The well insulated alternatives will have problems with over-temperatures which can possibly be solved by preventing insolation and more reduction of the internal heat gains.

Suggested further studies concern how air tight the building can get by performing certain measures, a deeper analysis of indoor comfort and evaluation of other wall renovation alternatives and combinations of measures.

Key words: Million homes programme, Record years, Peak years, Exterior wall renovation, energy improvement, LCC, energy efficiency,

Utvärdering av energieffektiviserande ytterväggsrenoveringslösningar för flerfamiljshus byggda 1961-1975

Examensarbete inom Building Performance Design

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Sammanfattning

Energieffektiviserande renoveringslösningar för ytterväggar studerades för ett typiskt flerfamiljshus från åren 1961-75. Renoveringslösningarna innefattar tilläggsisolering med mineralull och ny ventilerad fasad, förbättring av fönster och lufttätning. De utvärderades utifrån energieffektivitet, fuktsäkerhet, inomhuskomfort och kostnadseffektivitet. Resultaten kan komma att användas i utvecklingen av ett beslutsverktyg för fastighetsägare som ska renovera.

Husen från rekordåren (1969-75) har ett omfattande renoveringsbehov, vilket ger möjligheter att energieffektivisera kostnadseffektivt. Riksdagen har satt höga mål för den framtida energianvändningen i byggsektorn. Bra renoveringslösningar definieras som energi- och kostnadseffektiva, men de ska också vara också fuktsäkra samt medge bra inomhusklimat.

De studerade alternativen jämfördes genom att teoretiskt applicera dem på en verklig byggnad. Energiförbrukningen bedömdes genom beräkningar med dataprogrammet IDA. Köldbryggor behövs som indata och beräknades numeriskt under stationära förhållanden med Heat2. Värme- och fukttillståndet i väggen bedömdes med numeriska simuleringar i WUFI 1D. Kostnadseffektivitet utvärderades genom livscykelkostnadsberäkningar. Bedömning av värmekomfort inomhus grundades på operativa temperaturer, golvtemperaturer, strålningsasymmetri.

För att uppnå energimålen (halvering av energiförbrukningen) behöver flera byggnadsdelar åtgärdas och följden är svårigheter att nå kostnadseffektivitet. Dock är valet av indata, såsom energipris och energiprisökning avgörande och en liten förändring påverkar resultatet avsevärt. Halvering av energianvändningen kan uppnås till en lägre kostnad än för den utförda renoveringen i den verkliga byggnaden. De välisolerade alternativen kommer att få problem med övertemperaturer. För att lösa problemet krävs ytterligare åtgärder som begränsar internvärmen och solinstrålningen.

Förslag på fortsatta studier är: Hur god lufttäthet kan rimligen uppnås för olika renoveringsalternativ. Djupare analys av hur inomhusklimatet påverkas av renoveringen. Utvärdering av ytterligare väggrenoveringsalternativ och kombinationer av renoveringsåtgärder.

Nyckelord: Miljonprogrammet, Rekordåren, renovering av ytterväggar, energieffektivisering, LCC.

Contents

Preface

In this work calculations and s of energy, heat, moisture and cost has been carried out in order to make a theoretical evaluation and comparison of some renovation alternatives for exterior walls in a common multi-family house from the record years (1961-75). The study was made during the spring of 2011 and is performed in collaboration with a project called Renobuild with the aims to develop a renovation decision tool for building owners.

The work was initiated by Kristina Mjörnell at SP Technical Research Institute of Sweden, who also participates in Renobuild. Kristina Mjörnell is the MSc-thesis supervisor at SP and Bijan Adl-Zarrabi is the supervisor at Chalmers. Apart from Mjörnell and Zarrabi, Owe Svensson, Bertil Jonsson, Carl-Magnus Capener and Peter Ylmén at SP have been very helpful. I would also like to thank Jan Pettersson at WSP and Bengt Josefsson Alingsåshem for the supplied drawing material.

Göteborg August 2011

Mikael Eriksson Andin

1 Introduction

In the times of global warming and recourses running short, it is important to reduce the energy consumption in the society. The existing building stock consumes nearly 40% of the total energy in the society and the older houses are the largest consumers. Between 1960 and 1975 almost one million apartments were built in Sweden in order to provide modern homes to the increasing population. This is roughly one third of the total apartment stock. Today most of these multi-family houses are in need of substantial renovation which gives an opportunity for cost efficient energy improvements.

The Swedish parliament has set high goals for decreasing the energy consumption in the building sector. Improvements of technical systems are not enough to reach these goals. The building envelope must also be improved. However, many investigations show that renovations of the building envelope can become so costly that they won't be accomplished.

The largest heat loss in the studied buildings occurs via ventilation, the second largest through windows and finally the heat loss through exterior walls. Modern technology can reduce ventilation losses with 60-80% and window losses by more than half. Exterior walls can be improved by additional insulation and air tightening, but which are the best technical solutions is uncertain. Furthermore they need to be cost efficient while maintaining good qualities.

Some renovation measures for exterior walls in a common house type that was built during time period 1961-75 were evaluated in this work. The studied parameters were energy consumption, heat and moisture condition (to assess the durability), indoor thermal comfort and cost. The studied wall renovation measures are variations of additional mineral wool insulation with ventilated façade and different degree of demolition, air tightening and window upgrading.

The methodology is theoretical, based on literature studies and calculations. The results from the study can be used as a basis for a methodology for evaluation of different renovation alternatives.

The target group is students on the Civil engineer program, technical staff at housing owner companies, consultants, contractors and the Renobuild group.

1.1 Background

The Swedish parliament decided 1964 that one million homes should be constructed until 1974 in order to put an end to the housing crisis. The project is known as *the million homes programme*. However, the intensified house production had already started before the parliament's decision as increasingly industrialized construction methods were developed in the fifties and sixties. The time period 1961-75 is commonly referred to as *rekordåren* in Swedish and is translated to *the record years* in this work.

The buildings that were constructed during the record years are now facing extensive renovation needs. The water supply- and sewage pipes need to be replaced, there are moisture problems, facades are often damaged and there are comfort problems such as cold temperatures and draught.

An opportunity arises for additional energy saving renovations when making the necessary repairs. Comfort-enhancing and environmental-improving measures can get profitable if made in a smart way together with the necessary repairs (Gerdin & Hammarberg 2010)

1.1.1 Building stock and its condition

In 2002 there was about 830 000 apartments in multi-family houses constructed during 1961-75. This is approximately 35% of all apartments in multi-family houses. 710 000 of these, i.e. over 85% had not been renovated until 2002, see the circumscribed bar in Figure 1. The figure also clearly shows the production peak during the record years. In rough numbers 700 000 apartments are in need of extensive renovation the coming years. (Boverket 2003)

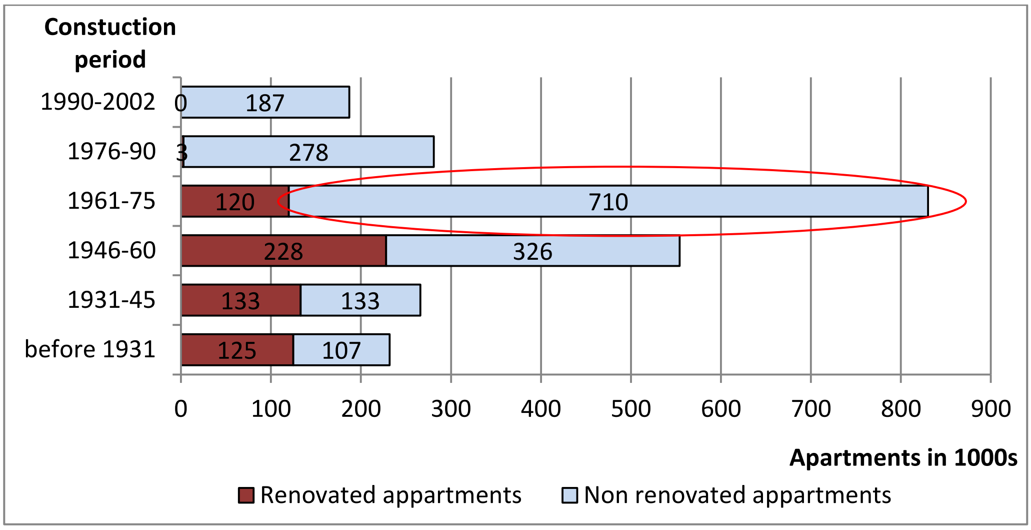

Figure 1. Renovated and non-renovated apartments in multi-family houses from different time periods in Sweden 2002 (Boverket 2003). The bar with apartments relevant for this study is circumscribed in red.

The different types of renovation that had been performed in the buildings from the record years are presented in Figure 2. It indicates that change to efficient windows and additional exterior wall insulation only had been done in approximately 5% of the apartments. No single measure had been done in more than 10% of the apartments.

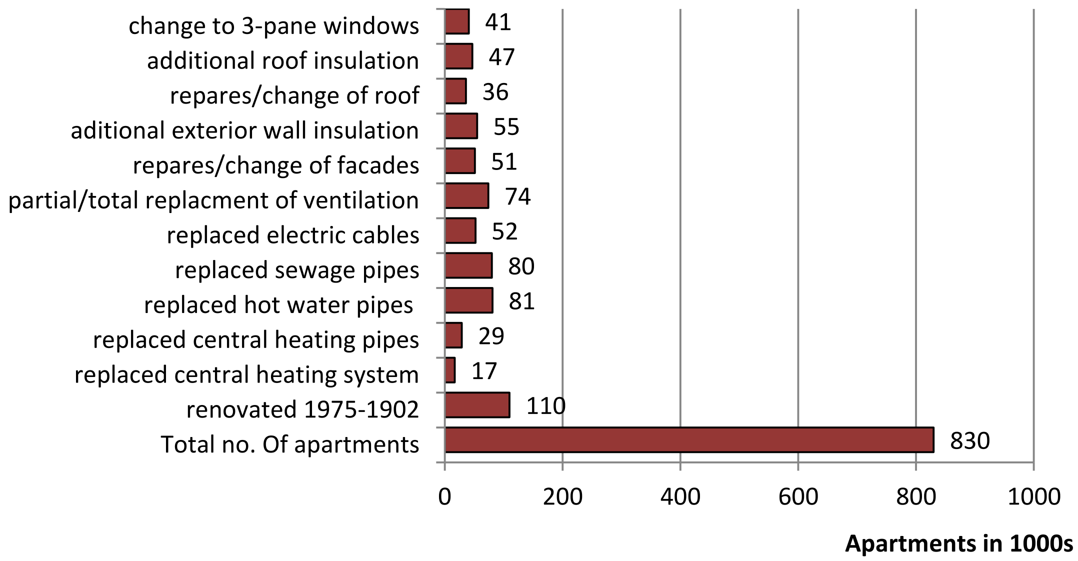

Figure 2. Renovation measures performed 1975-2002 on multi-family houses from the record years. Only 110 of 830 thousand apartments had been renovated until 2002. (Boverket 2003).

These statistics makes clear that there are many apartments left to renovate. The owners want cost effective measures and it is important for the society that the owners chose energy efficient measures. Solutions that are both cost effective and energy improving must be searched for. Different building types needs different measures for renovation. The next chapters is a survey of the most common building and wall types from the record years.

1.1.2 Building types

This chapter and chapter 1.1.3 are based on information from three sources (Bjerking 1978), (Björk, Kallstenius & Reppen 1983) and (Janson, Berggren & Sundqvist 2008).

The slab block is the most common type of multi-family house from the period. About half of all multi-family houses from the record years are three or four storey buildings of this type. The most common kind of slab block is three-storey's high with a load bearing concrete structure of book stack type, see Figure 3. "Book stack" is a direct translation from a Swedish concept that refers to the special load bearing structure similar to a book stack. The load is carried by transverse walls and the long sides of the building have infill walls. In the beginning of the period it was still common with load bearing exterior walls built of lightweight concrete but there was a change to concrete and light infill walls in the end of the sixties when the production peaked.

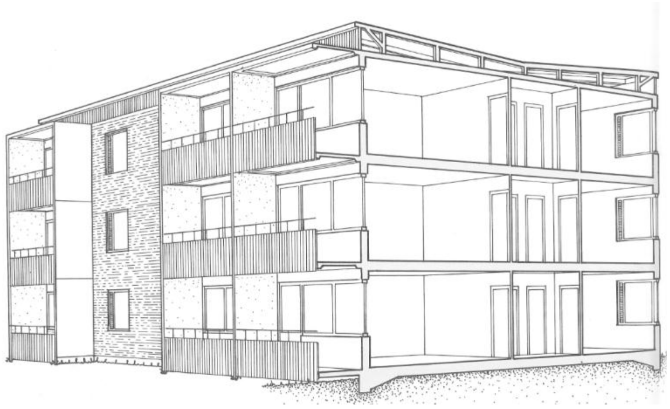

Figure 3. The common book stack structure with short side load bearing walls and infill walls between transverse load bearing interior walls on the long sides (Source: (Björk, Kallstenius & Reppen 1983)).

1.1.3 Wall constructions

The common load bearing walls and infill walls of houses from the record years have the following typical design:

- Load bearing concrete walls are usually insulated on the outside and clad with a weather-protective layer, commonly a brick cavity wall.
- External infill walls in the book stack structures have some typical compositions. One is timber frames with a façade of bricks, wood or weather boards. Another is rendered aerated concrete and a third is concrete sandwich elements.
- Concrete sandwich elements also appear in load bearing structures, in which case the inner concrete slab in the "sandwich" carries the load.
- Aerated concrete walls appear in load bearing structures. Sometimes alone and sometimes cast together with in-situ concrete on the inside. The aerated concrete blocks are usually covered with render and act as heat insulation.

Sufficient information is not available about how common the wall types are. There is however information which indicates that book stack structures are very common and those often have light timber framed infill walls. Brick is the most common façade material. Thus, it can be concluded that a book stack timber framed three storey slab block with brick façade is the most common type.

Typical problems with the walls are frost damages on bricks, air leakage causing draught and insufficient thermal insulation causing cold surfaces and high energy consumption.

1.2 Hypothesis

A proper wall renovation option can be found by studying some important factors. The chosen factors are; cost, energy efficiency, heat and moisture condition in the wall and thermal indoor climate. By assessing these factors it will be possible to find solutions that are economically viable, fulfil the energy goals, are durable and increase the wellbeing for the residents.

1.3 Aim of project

The aim was to choose and evaluate some relevant renovation options for the studied house type. The evaluation was based on the following factors; cost, energy efficiency, durability and indoor comfort.

1.4 Methodology

A pre study was made where empirical and statistical data was gathered and some rough calculations were made. The studied renovation alternatives were chosen based on this study. A reference building from a well-documented pilot project was chosen and the studied renovation alternatives were applied on a theoretical model of this building. The evaluated factors were then compared to measurements and theoretical calculations on the pilot renovation.

Material data such as heat and moisture properties are chosen as standard values according to praxis or by consulting experts. This study contains no measurements on real buildings. Theoretical, quantitative analyses based on calculations were made to find energy consumption, surface temperatures and cost. The assessment of indoor comfort had a more qualitative approach.

Several computer programs were used for the calculations. Thermal bridges were calculated with numerical steady state calculations in HEAT2, energy consumption and operative temperatures in IDA and heat and moisture condition the walls with WUFI 1D. A life cycle cost (LCC) analysis was carried out to assess the economic consequences of the renovation alternatives. The computer software Meteonorm was used to obtain the climate data used in the WUFI calculations.

1.5 Limitations

The study was based on the reference building located in Alingsås and its specific conditions. The studied wall renovation method was mineral wool additional insulation with a ventilated façade together with different degrees of demolition of the original construction. Additional measures included in the energy calculation were installation of a balanced ventilation system with a heat exchanger, installation of an exhaust air heat pump, air tightening, change to energy efficient windows, roof and ground additional insulation. Architectural, cultural and social aspects are not studied in this work.

2 Method for evaluation

The first step was to define a house type, in this case the most common one, and suitable renovation alternatives. A renovated reference building of the chosen house type was identified and the calculations were performed for this building's conditions with the intention to verify the results by comparing to measurements on the real building.

2.1 Course of action

The renovation alternatives were applied on a model of the real reference building. The model is a theoretical idealization of the real building in terms of material properties and geometry. Calculations were carried out on the model and data was obtained for the studied parameters according to the map in Figure 4.

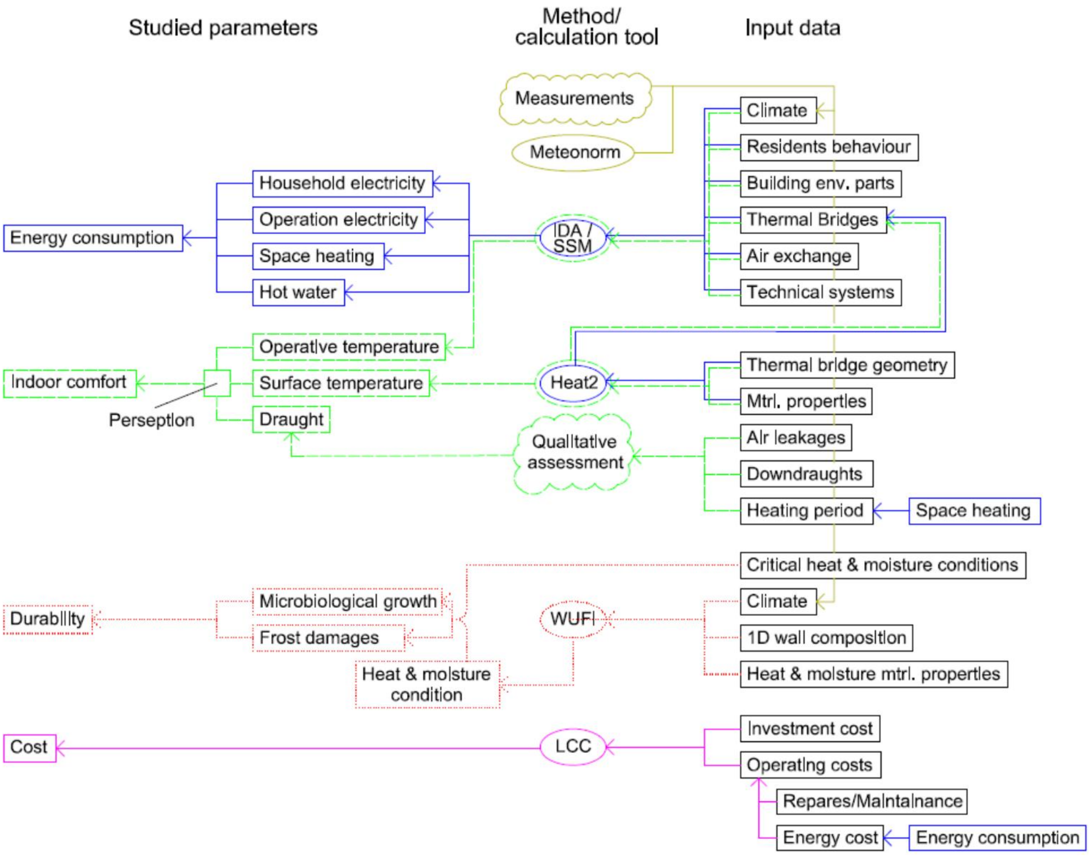

Figure 4. Execution map explaining how the studied parameters will be obtained using certain input data.

Renovation alternatives were selected among existing solutions. The reference building is from the housing estate Brogården in Alingsås and the specific house was chosen because it is representative for the studied house type and suitable to create a theoretical model after. This particular housing estate was selected because adequate data was available.

2.2 Calculation tools

The calculation tools have different degree of complexity and uses different mathematics. Here follows a brief description of how they obtain the studied parameters.

Table 1. Comparison of the complexity in the different calculation models

	SSM	IDA	WUFI	Heat 2
Mathematics	Network analysis*	Network analysis*	Numerical solution of 1D coupled PDE:s**	Numerical solution of 2D PDE**
Time dependance	Time independent	Time step: 1h	Time step: 1h	Time independent

SSM – Steady state model created in this work
IDA – Computer calculation tool for indoor climate and energy
WUFI – Computer calculation tool for heat and moisture in building components
Heat 2 – Computer calculation tool for 2D heat transfer.
* See (Hagentoft 2003) for explanation of thermal network analysis.
** PDE – Partial Differential Equation

Energy consumption was studied by making heat balance calculations for the building. The balance gives the necessary heat energy supply for a certain indoor air temperature and outdoor climate. IDA is a fairly sophisticated tool used in this work, but a less complicated steady state model that simplifies the reality more has also been used.

The steady state model (*SSM*) is a time independent energy model that uses annual mean temperature and does not consider thermal inertia of materials. The air leakage is an annual approximation based on the leakage at the pressurization of 50 Pa. In reality it strongly depends on ventilation, wind and stack effect. Though it is simple, it gives an estimation of the energy consumption that is good enough in many cases.

The software IDA provides a more sophisticated transient tool that can handle for example thermal inertia, insolation (thermal radiation coming in through windows) and impact of air leakage dependent on wind and stack effect. The model consists of connected component models, whose meaning in the model is defined by equations. As an example, a wall model consist of coupled components (material layers) with mathematically described physical properties. The same procedure applies to other building parts, thermal bridges, air leakages, and so on. All the component models are then coupled mathematically to constitute a zone. In turn the zone is coupled with other zones and a mathematical model of the building is created. Energy consumption and operative temperatures can be obtained by inserting input data such as climate, ventilation flows and internal loads for every time step during the calculation period.

Heat 2 was used to calculate thermal bridges. It is a numerical calculation tool for heat transfer in two dimensions. The energy models need the heat conductivity for all thermal bridges in a zone as an input.

Moisture safety was assessed with the software WUFI 1D, which is a tool for numerical calculation of the transient, one dimensional heat and moisture transport in multi-layer building components exposed to natural climate. Effective heat transfer for moist material can also be evaluated.

The *cost* of different alternatives is assessed by a Life Cycle Cost analysis based on the model from BELOK, Beställargruppen lokaler (Belok 2011). It is slightly modified to work with several energy types.

Indoor climate is assessed based on floor temperatures, operative and plane radiant temperatures and a qualitative assessment of risk of draught. Floor temperatures by beam foundation are calculated with a simplified hand calculation method from (Petersson 2007). Operative and plane radiant temperatures are calculated in IDA. Movement of cold air is not calculated, but qualitatively assessed based on air leakages through the building envelope and corresponding air temperatures.

3 The reference building

The chosen reference building is house J in Brogården. Brogården is a typical housing estate from *the record years* and was built 1971-73. It consists of 16 three storey buildings with brick façade and book stack structure.

Figure 5. Site plan, Brogården housing estate. The studied House J is marked.(Source: Alingsåshem AB)

A renovation is ongoing and it is planned to be completed in 2013. The first two renovated buildings were part of a pilot project and much effort was spent to achieve energy efficiency, increased well-being for the residents and increased accessibility. The aims were to achieve passive house standard. Figure 6 and Figure 7 shows the houses before and after renovation.

Figure 6. A house in Brogården before renovation (Source: Ulla Janson, LTH)

Figure 7. A house in Brogården after renovation. (Source: Ulla Janson, LTH)

Before the renovation the energy consumption was high. There were damages on bricks and balconies. Ground slabs were moisture damaged. The residents experienced draught and insufficient sound insulation and it was time to replace piping. Table 2 shows some results of the renovations in Brogården.

Table 2. Brogården before and after renovation according to (Mjörnell, Kovacs & Kyrkander 2010).

	Before	After
Building envelope parts	U-value [W/m^{2}K]	
Exterior walls	0.4	0.15
Windows	2.0	0.85
Roof	0.3	0.12
Ground	0.3*	0.25
Ventilation	Exhaust (no recovery)	Balanced (with HEX)
Air tightness	q_{50} [l/m^{2}s]	
Building envelope	2	0,3
Heating system	Energy type	
Space heating	District Heating	District Heating
Hot water	District Heating	District Heating
Energy Consumption	W/m^2,yr	
Space heating	115	19
Hot Water	42	18
Household electricity	39	28
Operation electricity	20	21
Total	216	86
* Calculated by the author according to EN 13370:1998		

The infill walls are completely demolished and replaced with new, very well insulated ones. The moisture safety and air tightness could be secured by using completely new infill walls and demolition. In the short side walls the load bearing concrete are kept and supplemented with significantly thicker insulation than before, matching the U-value of the light long side walls. The beam foundation is insulated on the outside and the original balconies cut off in line with the floor slab edge and new self-bearing ones built on the outside. As a result the thermal bridges decrease both in the balcony and in the wall since the inset balconies disappear as do the vertical corners at the balcony recesses and consequently its thermal bridges. The thicker wall insulation improves the thermal bridge by the floor slabs since the concrete is not as far out in the construction as before. Figure 8 shows the light infill wall and concrete wall before and after renovation.

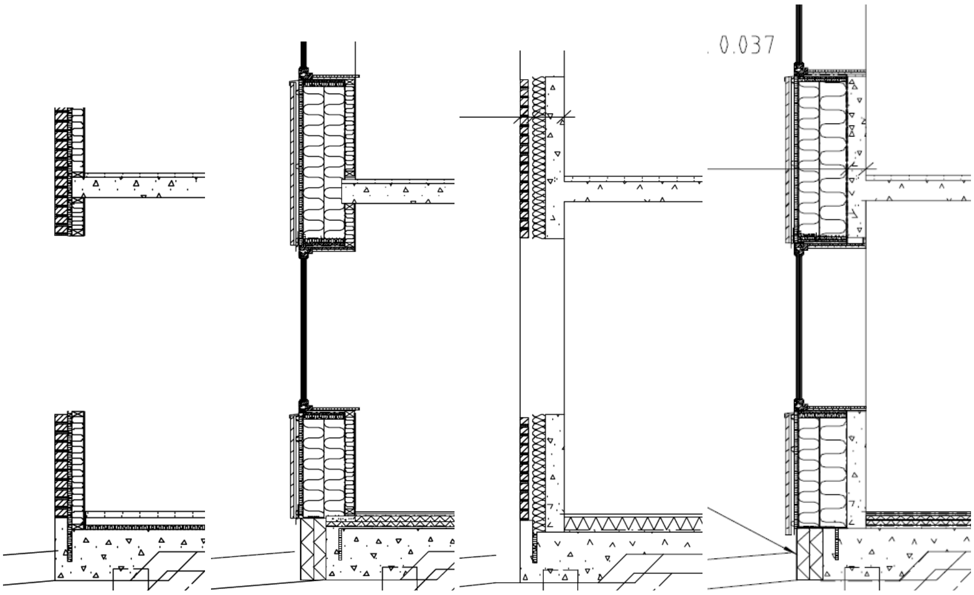

Figure 8. Brogården house J. Wall renovation in the pilot project. From left to right: Original infill wall, infill wall after renovation, original load bearing wall, load bearing wall after renovation.(source: WSP)

The current condition of the original plastic foil and hence the air tightness was uncertain, which was one of the reasons why the whole unit were replaced in Brogården. The material layers of the wall types can be seen in Table 3. New rational and industrialized methods were developed during the intensive production of houses when Brogården was built. One is the foliated gypsum board. It replaced the previous two installation stages of plastic foil and gypsum board with one.

Table 3. Material layers in original and renovated walls.

Infill wall		**Load bearing wall**	
Original	**Renovated**	**Original**	**Renovated**
13 foliated gypsum	13 gypsum	-	-
120 wooden studs/mineral wool	70 wooden studs/mineral wool	150 concrete	150 concrete
-	0,2 vapor barrier	-	0,2 vapor barrier
30 mineral wool	170 mineral wool	100 mineral wool	220 mineral wool
-	200 mineral wool + metal studs	-	200 mineral wool + metal studs
-	Air gap	Air gap	Air gap
120 brick leaf	22 brick screen	60 brick leaf	22 brick screen

4 Theory

This chapter contains a description of the theory behind the calculations of energy consumption, heat and moisture transfer, life cycle cost and assessment of indoor comfort.

4.1 Energy Consumption

The heat losses of a house are balanced by the supplied energy in order to keep the desired indoor temperature. This is called energy balance. The supply energy can be divided into two main parts based on its purpose: energy for heating and for powering equipment.

4.1.1 System boundary

In order to discuss energy leaving or entering a building, the system boundary must be defined. When looking at a house it is convenient to put the boundary at the building envelope. Boverket (the Swedish housing authority) has a definition according to Figure 9 which is also used in this work. The building´s energy consumption is shown as two arrows in the lower left corner.

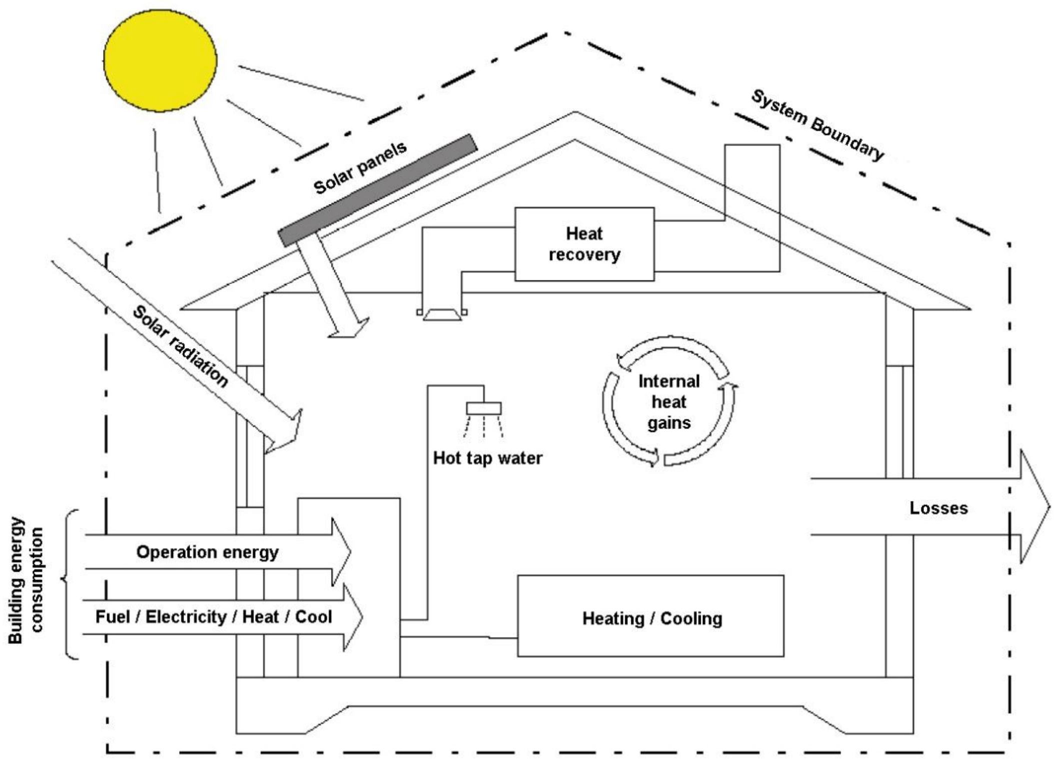

Figure 9 Boverket's definition of the system boundary. (The text in the figure is translated from Swedish by the author. The original figure appears in Boverket (2009))

4.1.2 Energy posts

Lost and supplied energy can be branched out into different posts. In Figure 9 the supply is illustrated as three arrows: *solar radiation*, *operation energy* and *Fuel/Electricity/Heat/Cool*. The losses are illustrated as one arrow called *losses*. A finer division is shown in Figure 10.

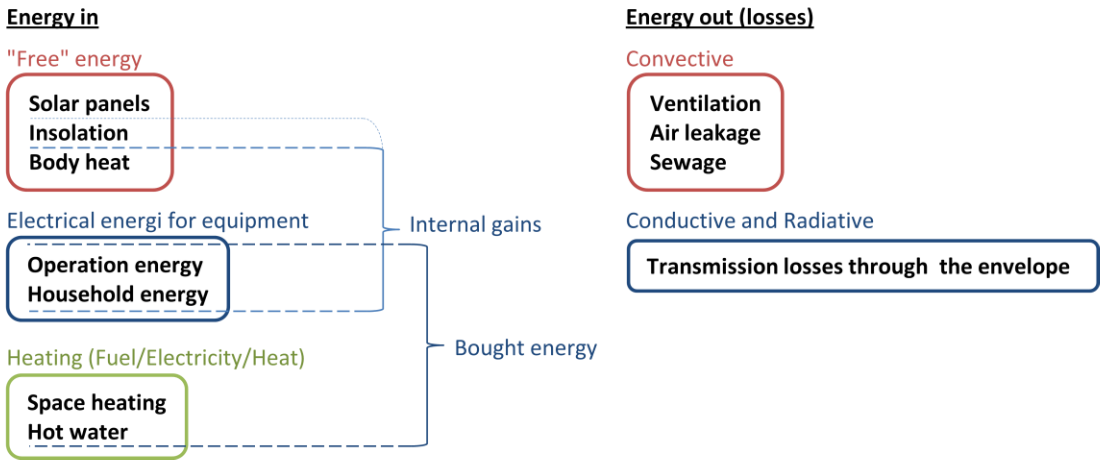

Figure 10. The most important energy posts going through the energy system boundary.

Bought energy is an economically important factor that is balanced by the *free energy* and the *losses*. The concept *Internal gains* sometimes include *insolation* and is important since it limits the need for heating during winter. However it might cause problems during summer by contributing to over-heating in well insulated houses.

4.1.3 Energy balance calculation

The energy consumption can be predicted by making an energy balance calculation. It can either be steady state (time independent) or transient (time dependent). The transient calculation is generally more accurate, but requires more input data. Both calculations are used in this work. The following energy posts are included in the energy balance.

4.1.3.1 Transmission losses through the building envelope

Heat losses due to transmission losses are calculated by:

$$\dot{Q}_{trans} = \left(\sum_i U_i \cdot A_i + \sum_j \Psi_j \cdot L_j\right) \cdot \Delta T = \quad [W] \qquad (4.1)$$

Where:

U is the one dimensional thermal transmittance of the building part *i* [W/(m²·K)]

A is the area of the building part *i* [m²]

Ψ is the transmittance of the linear thermal bridge *j* [W/(m·K)]

L is the length of the thermal bridge *j* [m]

ΔT is the temperature difference between indoor and outdoor [K or ˚C]

Three dimensional or point thermal bridges can also be included.

4.1.3.2 Ventilation and sewage losses

Heat losses due to fluids streaming through the boundary such as ventilation losses, air leakage and sewage losses, depend on the media's density, its thermal capacity, the volume flow and the temperature difference. Ventilation and air leakage losses are calculated as:

$$\dot{Q}_{vent} = \rho \cdot c_p \cdot \dot{V} \cdot \Delta T \quad [W] \qquad (4.2)$$

Where:

ρ is density of the media [kg/(m³)]

c_p is the thermal capacity [kJ/(kg·K)]

$\dot{V}$ is the volume flow [m³/s]

ΔT is the temperature difference between indoor and outdoor [K or ˚C]

If there is a heat exchanger in the ventilation system the losses will decrease depending on the temperature efficiency of the heat exchanger according to

$$\dot{Q}_{vent} = (1-\eta)\rho \cdot c_p \cdot \dot{V} \cdot \Delta T \quad [\mathrm{W}] \tag{4.3}$$

Where:

η is the temperature efficiency of the heat exchanger [-]

4.1.3.3 Air leakage losses

Air leakage is the consequence of a not air tight building envelope. In Sweden the air tightness is commonly described as the leakage per square meter when the building is pressurized at 50 Pa. For normal conditions the pressure difference over the building envelope is much lower. There are different ways to mathematically describe the relation between the leakage at 50 Pa a and leakage for normal conditions. One common way is the Persily-Kronvall estimation model that is modified by Elmroth (2009). It assumes that there is a linear relation between the leakage at 50 Pa and the annual leakage.

$$q_{leak} = \frac{q_{50}}{c} \quad [\mathrm{l/(s \cdot m^2)}] \tag{4.4}$$

Where:

q_{50} is the leakage per square meter envelope area at 50 Pa [l/(m^2·s)]

q_{leak} is the annual mean leakage per square meter envelope area [l/(m^2·s)]

c is a constant recommended to 20 for balanced ventilation and to 40 for mechanical exhaust ventilation. Some practicing engineers use 25 for both cases (Berge 2011).

Another more accurate model is the power law. It describes the relation between the pressure difference and the leakage. This mathematic relation is used by IDA for each timestep.

$$\dot{V} = C(\Delta P)^n \ [\mathrm{m^3/s}] \tag{4.5}$$

Where:

$\dot{V}$ is the air volume flow [m^3/s]

C is a leakage constant [m^3/(s·Pa^n)]

ΔP is the pressure difference over the building envelope [Pa]

n is the an exponent, set to 0.65 based on experience according to Svensson [1]

By using the leakage per square meter at 50 Pa, the leakage constant, C is obtained according to:

$$C_{leak} = \frac{\dot{V}}{\Delta P^n} = \frac{q_{50} A_{env}}{\Delta P^n} \quad [\mathrm{m^3/(s \cdot Pa^n)}] \tag{4.6}$$

Where:

q_{50} is measured leakage per square meter [l/s/m^2]

A_{env} is the inside envelope area including walls, roof, ground floor, windows and doors [m^2] according EN 13829:2000.

The total leakage might occur through many leakages that will all contribute to the flow:

$$\dot{V}_{tot} = \sum_i C_i(\Delta P_i)^{n_i} = (C_1 + C_2 + C_n)\sum_i(\Delta P_i)^{n_i} = C_{tot}\sum_i(\Delta P_i)^{n_i} \tag{4.7}$$

[1] Owe Svensson, engineer at SP Technical Research Institute of Sweden, telephone conversation April 2011.

The pressure difference over the wall can be calculated as a combination of the pressure caused by wind, stack effect and mechanical ventilation:

$$\Delta P = \Delta P_w + \Delta P_s + \Delta P_v \text{ [Pa]} \tag{4.8}$$

Pressure imposed by wind depends on the wind speed (which in turn depends on the height) and wind direction. The wind pressure acting on any point at a façade can be described by:

$$P_w = C_p \frac{\rho_a v^2}{2} \tag{4.9}$$

Where:
P_w is the wind pressure [Pa]
C_p is a wind pressure coefficient [-]
ρ_a is the density of air [kg/m^3]
v is the wind speed [m/s]

The wind pressure coefficient is averaged for each building face in the calculations. It is set according to Figure 11 based on (ASHRAE 2009 chapter 14)

ϴ	f1	f2	f3	f4
0	0.4	-0.3	-0.	-0.3
45	0.1	0.1	-0.35	-0.35
90	-0.3	0.4	-0.3	-0.2
35	-0.35	0.1	0.1	-0.35
180	-0.2	-0.3	0.4	-0.3
22	-0.35	-0.35	0.1	0.1
270	-0.3	-0.2	-0.3	0.4
315	0.1	-0.35	-0.3	0.1

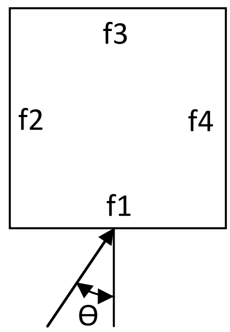

Figure 11. Wind pressure coefficient Cp for low rise buildings, upp to three storeys, expressed as an average value for each face of the building.

The exact leakage distribution over the building envelope is not known. In this work it was assumed that the infiltration occurs only through the exterior walls and that all four walls had equal leakages. The total leakage constant C was calculated by equation (4-10) and divided evenly on 12 leakages, as shown in Figure 12. Hence, each leakage will get the constant $C_n = C_{tot}/12$.

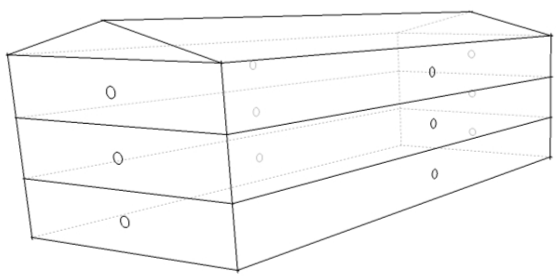

Figure 12. The leakage distribution as assumed in the energy calculation. Every storey has four leakages, one on each exterior wall. In total 12 identical leakages.

If the house has a mechanical exhaust ventilation system, there will be ventholes in the facade that influence the tightness. The characteristics of these holes were estimated by setting a desired under-pressure in the building while assuming no unintended leakage through the envelope. Equation (4.5) gives:

$$C_{ventholes} = \frac{\dot{V}}{(\Delta P)^n} \tag{4.10}$$

Where:
$\dot{V}$ is the air volume flow set to $0.35 \cdot A_{temp}$ [m^3/s]
ΔP is the desired pressure difference over the building envelope set to 7 [Pa]
n is the exponent set to 0.65

This way the ventholes can be considered by adding the leakage and venthole characteristics according to:

$$\dot{V}_{tot} = \sum_i \left(\left(C_{i,leak} + C_{i,venthole} \right) \Delta P_i \right)^{n_i} \right) \tag{4.11}$$

4.1.3.4 Internal gains

The internal gains depend on the activities in the building. In this work they include gains from people, equipment and hot water. The following approximation is suggested by Petersson (2007) and is used in the steady state calculation.

$$\dot{Q}_{gain} = \dot{Q}_{people} + 0{,}8 \cdot \dot{Q}_{household} + 0{,}2 \cdot \dot{Q}_{hw} \text{ [W]} \tag{4.12}$$

Where:
$\dot{Q}_{people}$ is the gain from people [W]
$\dot{Q}_{household}$ is the household electricity [W]
$\dot{Q}_{hw}$ is the hot water consumption [W]

In the transient calculation (IDA) the gain from people was calculated from metabolic rate (Met) and clothing values (Clo).

4.1.3.5 Solar radiation

Solar radiation affects the heat balance in two ways. It causes insolation through windows that give a heat gain inside. It also raises the temperature at the building envelope surface, which decreases the temperature difference over the wall during cold days. Consequently, the transmission loss decreases.

Insolation through windows depends on:

- The window area.
- The glass transmittance
- The direct and diffuse solar radiation, which in turn depends on how the sun and window face are directed as well as shading.

The direct radiation transmittance depends on the insolation angle. Diffuse radiation on the other hand is as strong in all directions and has therefore the mean transmittance for all angles. Following equation describe the heat gain through a window due to radiation:

$$\dot{Q}_s = A_{diffuse} \cdot g_{mean} \cdot I_{S,diffuse} + A_{direct} \cdot g_{direct}(\beta) \cdot I_{S,direct} \text{ [W]} \tag{4.13}$$

Where:

$A_{diffuse}$	is the area of the window [m^2]
g_{mean}	is the mean transmittance (for all angles) [-]
$I_{S,diffuse}$	is the solar radiation on a vertical surface [W/m^2]
A_{direct}	is the area of the window exposed to direct radiation [m^2]

g_{mean}	is the direct transmittance [-]
β	is the insolation angle [rad or °]
$I_{S,diffuse}$	is the solar radiation on a vertical surface [W/m^2]

The surface temperature on a wall depends on the radiation, heat and moisture conditions. In order to handle both radiative, conductive and latent heat transfer in the same calculation the concepts equivalent temperature and equivalent conductance was introduced. See (Hagentoft 2001, chapter 3.7) for more information.

4.1.3.6 Heat storage

Buildings thermal mass includes their ability to store heat during the heating period and release it again when the temperature is lower than the temperature of the material. Heat storage was only considered in the transient calculation. It has no effect during steady state conditions.

4.2 Heat and moisture transfer (WUFI)

The durability of a building element depends strongly on the heat and moisture conditions in the materials. Disadvantageous conditions can give microbiological growth and frost damages. The moisture condition also affects the heat transfer. The U-values used for energy calculations are normally calculated for dry conditions (which is also the case in this work). In order to assess durability and "wet" heat transfer the heat and moisture condition in the materials must be studied together over time which is rather complicated when considering the climate variations and the different kinds of transport and storage of heat and moisture.

Heat transfers by different mechanisms and can also be stored in a material.

Heat transport mechanisms (and driving potential):

- Conduction (Temperature)
- Radiation (Temperature^4)
- Convection (Pressure and density differences)
- Latent heat flow (Vapor diffusion)

Different kind of heat storage in a material:

- Storage in the dry material
- Storage in water in the material
- Storage because of phase changes (e.g. ice ↔ water ↔ vapor)

Moisture transport and storage mechanisms are similar to those of heat.

Vapor transport mechanisms (and driving potential):

- Diffusion (Partial vapor pressure)
- Convection (Pressure and density differences)

Vapor storage

- Adsorption

Liquid transport mechanisms (and driving potential):

- Capillary conduction (Capillary suction)
- Surface diffusion (Sorption layer thickness)

The heat transfer and moisture transfer depend on each other. The WUFI software couples their differential equations and calculates the transient heat and moisture conditions numerically, see Figure 13 and Figure 14.

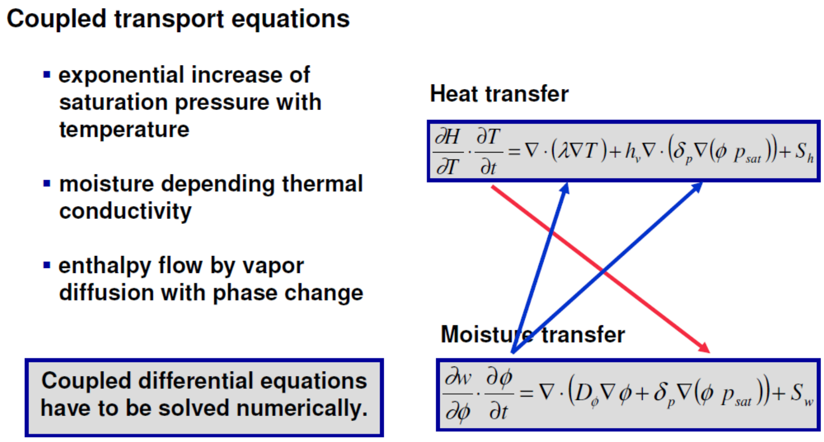

Figure 13. The dependence between the moisture transfer differential equation and the heat transfer differential equation. The arrows shows how they are coupled. (Source WUFI, Fraunhofer IBP)

Using the geometry, material properties, initial heat and moisture conditions and climate variations as input data, heat and moisture profiles and fluxes is obtained, see Figure 14.

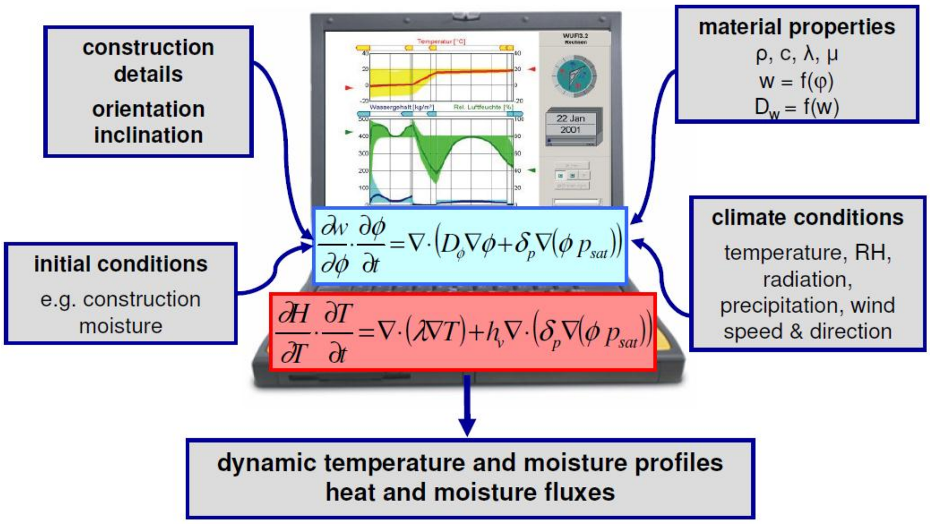

Figure 14. Inputs and outputs in the heat and moisture calculation.

4.3 Life Cycle Cost

The LCC method is used to calculate the total cost of the building during its lifetime, Total cost = Investment cost + Operation cost. Different alternatives can be compared and the alternative with lowest cost chosen. Future costs must be converted to a present cost which demands that an interest rate is chosen. Its size states how future gains are valued compared to having the money today. LCC in this work is calculated according to equations (4.14 – 4.17) based on the model from BELOK (Belok 2010) but slightly modified in order to work with several energy types.

$$r_r = \frac{(1+r_n)}{(1+q)} - 1 \approx r_n - q \tag{4.14}$$

$$v = \frac{(1+i)}{(1+r_r)} \quad (4.15)$$

$$B_o = b\frac{v(v^n - 1)}{(v-1)} \quad (4.16)$$

$$LCC = A_o + B_o \quad (4.17)$$

Where:
r_r is the real interest rate [-]
r_n is the nominal interest rate (the chosen interest rate) [-]
q is the annual inflation [-]
i is the annual energy price increase [-]
b is the energy cost the first year [SEK]
n is the chosen life span in years [y]
B_o is the present value of the accumulated energy cost [SEK]
A_o is the investment cost [SEK]

4.4 Indoor comfort

EN ISO 7730:2005 has recommendations for the thermal indoor climate during winter and summer. The parameters that are assessed in this work and its recommendations are stated in Table 4.

Table 4. Recommendations for indoor thermal comfort in dwelling houses.

Operative temperature °C		**Floor temperature °C**	**Radiant temperature asymmetry °C**			
Summer	Winter		Warm ceiling	Cool wall	Cool ceiling	Warm wall
23-26	20-24	19-26	<5	<10	<14	<23

5 Considerations when choosing renovation measures

There is plenty of energy saving and comfort enhancing measures available that can be done in addition to the necessary repairs. The best combination of measures depends on the buildings condition, the financial situation and the targets of the renovation. Previous renovations might also affect if a wall renovation measure is appropriate or not.

Different energy improving measures have different potential to reduce the consumption. The most efficient ones should be done first. Both energy consumption and cost must be considered when assessing the efficiency of the renovation.

Though not considered in this work, aesthetic, ecological and social values are important when evaluating the renovation options.

5.1 Technical condition of the building

The condition of the building is crucial when deciding what renovation measures to take. Each case is special. The most advantageous combination of measures depends very much on what needs to be done to reach the lowest acceptable level of performance. These necessary interventions in the building might make supplementary renovations reasonable. For example if the building is in good shape and a high energy consumption is the single renovation reason, it could be advisable to avoid extensive renovation and focus on optimizing the installations or install heat recovery etc. If the building on the other hand is damaged and needs extensive renovation, it is wise to carefully review the renovation options in order to find an environmentally friendly and long-term cost effective solution.

The external walls of the studied buildings have three main problems: air leakage, bad insulation and damages on the façade.

Air leakage occurs in joints and through holes in the vapor barrier. It causes heat losses and draught. Tightening the joints will improve the air tightness. Degenerated vapor barriers could be a source for leakages, but if it is a general problem is hard to say, since this hasn´t been studied.

The existing insulation might have degenerated. It is also thin compared to today's standards and there are big thermal bridges. The heat transmission can be decreased by adding insulation on the wall and by minimizing the thermal bridges. External additional insulation is recommended for moisture safety reasons and because it decrease thermal bridges better. Internal additional insulation is advised against by the same reasons.

The façade is often damaged and the problems are usually related to moisture and frost. If the damages are extensive the masonry veneer facade needs to be replaced and it becomes cost effective to put extra insulation in the wall. There are different options for insulation type and thickness, and façade materials.

5.2 The owners financial situation

What level of renovation is achievable depends on the owner's financial situation. In the report "*Hem för miljoner*" Sveriges Allmännyttiga Bostadsföretag, SABO (2009) states four levels for the record year houses:

1. **Full renovation**. The house gets, in principle, new construction standard. Installations are replaced and supplemented, kitchens and bathrooms renovated. Measures are taken for better accessibility, environmentally friendly solutions and energy efficiency. Exterior renovation provides better outdoor environment. Cost estimation: 12 000 SEK / m².
2. **Limited renovation**. Renovation of certain parts. Necessary technical upgrading of installations, in particular, new plumbing, kitchens, bathrooms, roofs and facades. Limited measures for improving availability and use of resources. Cost estimation: 6000 SEK / m².
3. **Minimal renovation**. Fix the technical defects that are unacceptable to the residents, causes the company substantial costs or jeopardize the survival of the building. Methods that minimize interventions are chosen. Cost estimation: 2000 SEK / m².
4. **Demolition.** Applicable mainly to declining markets. Cost estimation: 1000-3000 SEK / m².

In order to obtain cost efficiency the building's condition must be carefully investigated before choosing the level and measures for the renovation. After finding which the necessary repairs are, a smart combination of additional renovation measures can be decided.

5.3 Renovation concepts

Some kind of concept and aims are needed in order to decide what measures to perform. The ambitions could be to lower the operation cost, create more rentable space, increase the accessibility, decrease the buildings environmental load, improve the aesthetic appearance etc. It is desirable to find the combination of measures that fits best with these aims and at the same time is financially feasible. If there is no concept or plan, there is a great risk that other renovation needs appears later when it will be very cost inefficient to perform them.

One clearly defined concept is passive house renovation. The term passive house (*Passivhaus* in German) refers to the rigorous *Passivhaus* standard for energy efficiency in a building. There are other similar standards such as the Swiss *Minergie-P*, but the Passivhaus standard has become popular and well known in Sweden. There are regional differences in the standard but the main criteria to be certified as Passivhaus is low enough annual energy consumption and heat effect while maintaining good indoor comfort (FEBY 2009).

5.4 Improving the energy performance

In the cold climate of Sweden the most important action to lower the energy consumption is to reduce heat losses such as ventilation and sewage losses by using *heat recovery* in form of heat exchangers or heat pumps, air leakage by improving the *air tightness* of the envelope and heat losses through the envelope by *better insulation*. When this is done the *technical systems* should be optimized and adjusted.

The typical three storey house from the record years has in principle the following characteristics. Modern house standard are presented in brackets:

- External wall insulation thickness of 10 cm (20 cm)
- Roof insulation thickness of 15 cm (40 cm)
- Window U-value of about 3 W/m^{2}K (0.9-1.2 W/m^{2}K)

- Natural ventilation or mechanical exhaust air (mechanical supply and exhaust air with heat exchanger)
- Indoor temperatures often vary between apartments. When one apartment is to cold another might need to divert heat.
- The hot water consumption is high compared to modern houses.

Catarina Warfvinge, Assistant Environmental Manager at Bengt Dahlgren AB and lector at Faculty of Engineering, LTH, has made energy calculations for a typical three storey slab block with bock stack structure and she suggest a five step program for energy improvement of these houses (Warfvinge 2008).

1. **Improve the building envelope**
   Start to make the house more airtight by fixing leakages. Change or improve the windows to lower their U-values. Add insulation. It is often worthwhile to increase the 15 cm insulation on the loft floor. The exterior walls are often so costly to insulate additionally, that it only pays of when the facade needs to be changed for maintenance reasons.
2. **Improve the ventilation system**
   Next step is to recover heat in the ventilation air. This is not possible for natural ventilation. For a mechanical exhaust air system it is possible to install a heat pump that will save a lot of energy but also need electrical power. If instead a mechanical supply and exhaust air system with heat exchanger is installed the energy savings are significant.
3. **Adjust the heating system**
   The heating system must be adapted to the new lower heating need. There is a regular need for adjustments anyway, but after measure 1 and 2 there will be less cold surfaces and air movements indoors. Consequently it is possible to lower the mean temperature in the building and save energy without causing comfort problems.
4. **Decrease the hot water consumption**
   By using low flow nozzles the hot water consumption can be decreased considerably. Another way to lower it is to start using individual billing of hot water.
5. **More actions**
   The possibility to add insulation to the exterior walls can be used. If the façade needs to be changed it is a good idea to take the opportunity and add a considerable amount of insulation. It might be 50 years till the next chance occurs. Installing solar panels lowers the energy for hot water production. Individual billing of electricity will decrease the household energy with 10 $kWh/(m^{2\cdot}A_{temp})$.

The reduction in energy consumption was d by Warfvinge for each step. The result is shown in Figure 15.

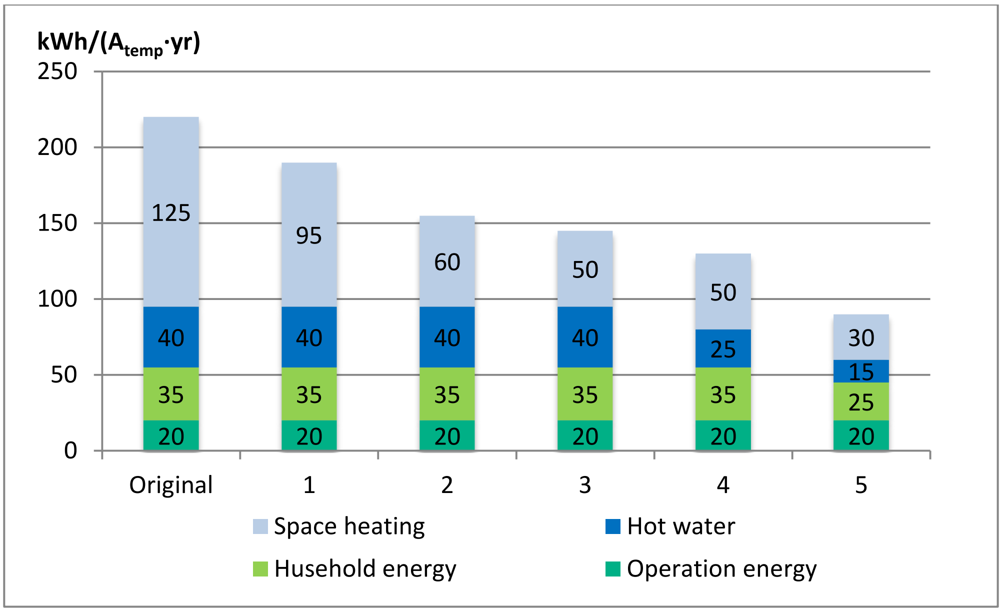

Figure 15. The reduction of bought energy for each of Warfvinge's (2008) renovation steps.

Examples of alternatives that Warfvinge doesn't mention is; heat recovery on sewage, toilets consuming very little water, more efficient electrical equipment, demand controlled ventilation, circulation of hot water (that prevents unnecessary water usage when waiting for hot water) and ground insulation.

Another option that could be economically interesting is to create extra space to rent out. It is common to create new indoor space in connection with the balconies. In some cases it is possible to build a whole new storey on top of the old house, but the studied three storey houses are often very well optimized and cannot carry the weight of an extra storey.

5.5 Cost efficiency

An LCC analysis was made for an existing three storey multi-family house in Malmö, by Janson, Berggren and Sundqvist (2008). The house was built around 1965 and is similar to the house type studied in this report. The investment cost was estimated by experienced calculators at Skanska AB and the service life cost is approximated as the cost of the consumed energy. The results from their LCC for a service life of 30 years are shown in Figure 16. Bars concerning wall renovation are colored green and bars concerning renovation with multiple measures are colored dark green. The result is shown in Figure 16. See paragraph 7.11 for input data.

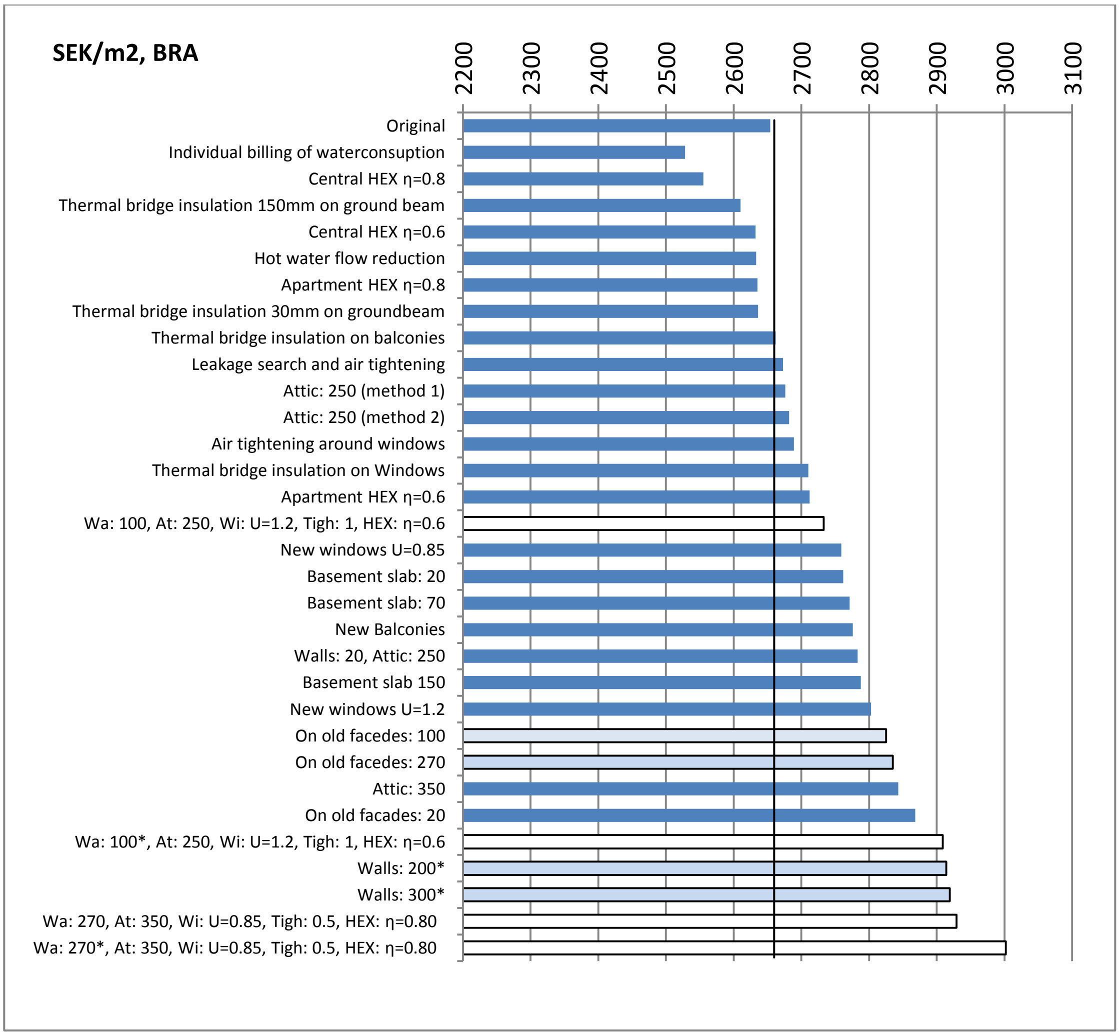

*Figure 16. Result of the LCC calculation for 30 years made in (Janson, Berggren, Sundqvist 2008). The vertical line shows the cost/m² living area if nothing is done. Bars with black edges indicates that something is done with the wall, white filling indicates a single measure and light blue filling a combination of measures. The sign * means that the original façade is demolished. Just a number refer to thickness of additional insulation. Wa=Wall, At=Attic, Wi=Windows, Tigh=Air tightness (in $l/(s{\cdot}m^2)$ at ΔP=50 Pa)*

The calculation shows that, individual billing of water consumption, installing water flow reductive equipment and installing heat exchanger on the ventilation are cost effective single measures. It is however not cost effective to insulate the walls.

The choice of life span 30 years is questionable since the house probably will be used for more than 30 years after the renovation. Perhaps the life span should be longer. Another important note about the calculation is that the benefit of each renovation measure is only measured in reduced energy cost. If repairs are needed because of damages or abrasion there are obvious benefits (functionality, comfort, aesthetics, etc.) that are not shown in the calculation.

The input data is of great importance to the results but not so easy to choose. It could be reasonable to use a life span of 50 years which means that the energy price during the coming 50 years must be estimated. This is of course very uncertain.

5.6 Aesthetic, ecologic and social values

The Swedish Planning and Building act demands that buildings shall be given an aesthetically pleasing appearance in color and shape. Care shall be taken to retain the building's characteristics when upgrading. The aesthetic requirements should be based on values with a high general acceptance (Vidén & Botta 2006).

Energy consumption during service life is not the only environmentally important factor when renovating. Consideration should also be taken to the impact during construction and from materials. Waste management is another important factor that can often be improved.

Social values might be important to consider. One such value is increased accessibility. Adaption for disabled people is one way of doing that. Other social values are increased well-being or decreased anxiety that could be affected by architecture. In the case of facades it may mean choosing materials that age well, are easy to maintain and won’t get dirty.

6 Results of the pre study

The choice of renovation options and combinations evaluated in this work are based on the pre-study that is presented in the background chapter and chapter 5. Here follows further results from the literature study and the results of the rough calculations that were carried out before the final calculations.

Four categories of renovation combinations were selected for further, more detailed investigations. Each category contains renovation combinations where some measures are fixed and some measures vary. The main variation concerned wall renovation.

When doing a renovation with aims to save energy, it is advisable to first deal with the losses from ventilation and windows. This is shown by previous investigations such as Warfvinge's (2008) and Janson, Berggren & Sundqvist's (2008). Except from the walls, measures concerning air exchange and windows are also described in the following chapters, since the choice of wall renovation affects the air tightness and the windows conditions might affect the choice of wall renovation.

6.1 Windows

Windows contribute to a large part of the building´s transmission losses. Although they often represent a small portion of the façade, the losses are often bigger than through the walls since their U-values are about 10 times larger than for the walls. Original windows from 1961-75 usually have a U-value between 2 and 3 W/m^{2}K. [2]

One way of decreasing the heat loss is to change the windows. New energy efficient windows have U-values less than 1 W/m^{2}K. Another way is to make them more energy efficient by changing one of the two panes to a more energy efficient pane. Measurements made by SP Technical Research Institute of Sweden show that the U-value can decrease from 2.8 to between 1.9 and 1.3 by such measures. (Energimyndigheten 2008).

Just replacing the old windows (U=2 W/m^{2}K) with new (U=1 W/m^{2}K) would give energy savings of 17 kWh/m^2/yr in the reference building according to the steady state model.

Window change or renovation affects the façade's appearance and it must be assessed if the new appearance is acceptable.

Insolation through windows is often desirable during winter but can cause a heat surplus during summer resulting in overheating problems. Calculations show that the solar heat gain during the heating period for Brogården pilot is approximately 5200 kWh ~ 5kWh/m^2/yr.

6.2 Air exchange

Fresh air is needed in the house, but blowing out warm used air and taking in cold fresh air gives major heat losses. One part of the air exchange is the intended ventilation. If there is a mechanical ventilation system this part can be controlled by fans and dampers and its heat can be recovered. The other part is unintended leakage that cannot be controlled.

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[2] *Bertil Jonsson*, senior researcher at SP Technical Research Institute of Sweden, telephone conversation May 2011.

6.2.1 Ventilation

The recommended hygiene ventilation flow is 0.35 l/(m^2s) for dwelling houses in Sweden. For a mean outdoor temperature of 7°C and an indoor temperature of 22°C this flow gives ventilation losses of 55 kWh/m^2/yr. For old multi-family houses the ventilation is often unbalanced and set to high which leads to even bigger heat losses and indoor climate discomfort. Balancing the flow by adjusting the dampers and installing heat recovery will improve the condition.

One way to recover the exhaust air heat is to install a heat pump. Then the heat in the exhaust air can be used to heat for example the hot water. On the downside the process uses electrical energy. The coefficient of performance (COP) for exhaust air heat pumps is around 2.5-3 over the year which means, that for every kilowatt-hour electrical energy fed to the pump 2.5-3 kilowatt-hours are gained in heat energy.

Lindblom (2008) has made an investigation of energy saving measures for existing multi-family houses. He found that an exhaust air heat pump would reduce the heat loss with 130 MWh per year and m^3/s ventilation flow, and increase the use of electricity with 130/3=43.3 MWh per year and m^3/s ventilation flow. The assessment was made for the existing housing estate *kv. Ripan* in Solna which consist of nine 3-6-storey brick houses built around 1950. For a ventilation flow of 0.35 l/(m^2s) the amount of energy translates to a heat loss decrease with 45,5 kWh/m^2/yr and electricity consumption increase with 15,2 kWh/m^2/yr.

An exhaust air heat pump is generally used together with exhaust ventilation where the fresh air is taken in through inlets behind the radiators where it is heated. In very well insulated houses with exhaust ventilation, where the radiators are turned off during many cold days, residents have experienced draught because of the cold air coming in. This fact suggests that a heat exchanger is a better choice than an exhaust air heat pump for very well insulated houses.

A heat exchanger uses the warm exhaust air to heat the cold supply air with efficiencies of about 0.6-0.8 which gives a theoretical heat loss reduction of 33-44 kWh/m^2/yr.

6.2.2 Leakage

The unintended leakage is not necessarily bad for the energy consumption. Consider a mechanical exhaust air system: It will not cost more energy to heat the air that leaks in than the air that enters through ventholes. The problem is that the air that leaks in won't be heated by the radiators, which creates a comfort problem. Another problem is that a certain amount of air also will leak out which increases the air exchange and consequently, the heating energy.

For balanced ventilation (exhaust and supply fan), which is used together with a heat exchanger, the indoor and outdoor pressure will in principle be the same. Due to wind and stack effect however, some parts of the building envelope will be subjected to suction from the outside and other parts to suction from the inside. This causes an unintended air exchange with no heat recovery which is directly dependent on the air tightness of the building envelope.

Different combinations of air tightness, ventilations system and heat recovery were calculated in IDA. The resulting energy consumptions are shown in Figure 17.

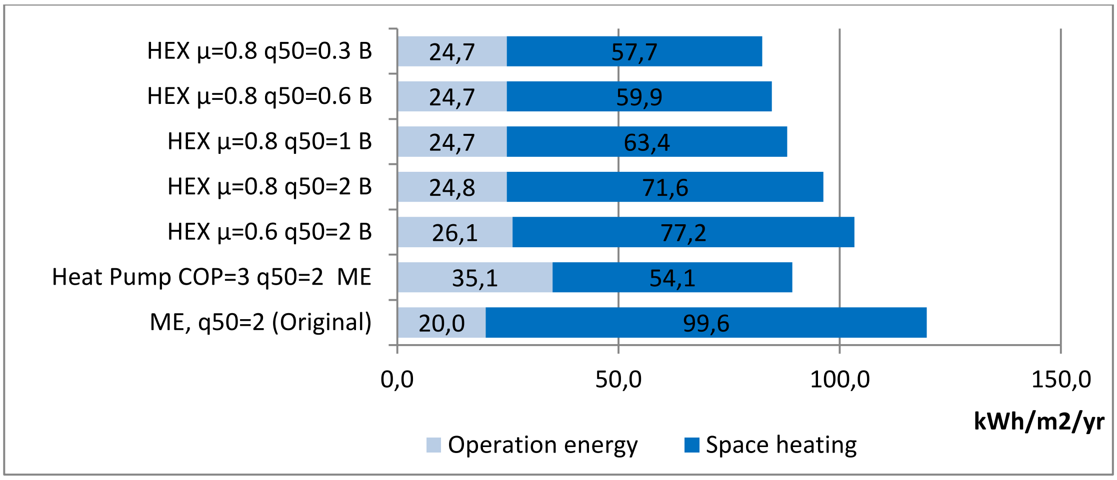

Figure 17. Comparison of different options related to air exchange. HEX=Heat exchanger, B=Balanced ventilation, ME=Mechanichal exhaust air

Installing heat recovery together with air tightening has a great energy reducing potential. The big difference between a heat exchanger and a heat pump is the ratio of *operation electricity* and *space heating*. The heat pump needs Prices and environmental loads for different energy types must be considered before choosing between heat exchanger and exhaust air heat pump. Further, draught problems aren't solved with a heat pump but its installation requires less intervention in the building than a balanced ventilation system.

Table 5 shows the economic importance of air tightness in terms of the economic savings when improving the air tightness from a specific infiltration rate q_{50} to a lower. The table is based on the results in Figure 17 and calculated for an energy price of 1 SEK/kWh.

Table 5. Savings per year when improving air tightness together with a balanced ventilation system.

		Savings in SEK per year and m^2				Savings in SEK per year (A=1016 m^2)			
		New infiltration rate, q_{50}				New infiltration rate, q_{50}			
		2	**1**	**0,6**	**0,3**	**2**	**1**	**0,6**	**0,3**
Original q_{50}	**2**	0	8,2	11,7	13,9	0	8331	11887	14122
	1	-	0	3,5	5,7	-	0	3556	5791
	0,6	-	-	0	2,2	-	-	0	2235

An issue that couldn't be answered is how tight the envelope must be in order to avoid comfort problems.

6.3 Insulation material

Mineral wool is the only studied insulation material in this work. The renovation method with additional mineral wool insulation and a façade board with an air gap is a solution that has proven to be moisture safe. Other traditional materials that could be used are glass wool and cellular plastic. High performance thermal insulation (HiPTI) such as vacuum insulation panels (VIP) and aerogel blankets are included in the following chapter, but apart from that they are not considered in this work.

6.4 Internal insulation

Internal insulation is often not recommended because it can lead to moisture problems in the wall. Sometimes however, it is the only option, for example when the exterior façade cannot be changed. It can also function as an installation layer that will prevent penetrations of the air tight layer and eventually improve the air tightness.

There is a discussion whether it is economical or not to insulate internally. The rentable space will decrease and therefore this alternative becomes less profitable. A rough calculation for the reference building showed that with today's prices it is difficult to save money by insulating internally. The results and the input data are shown in Figure 18 and Table 6. In Sweden today the mean rent per square meter is around 800-900 SEK/(m^2year). The energy price varies below 1 SEK/kWh. (SCB 2011). Investment cost was not considered in the calculation.

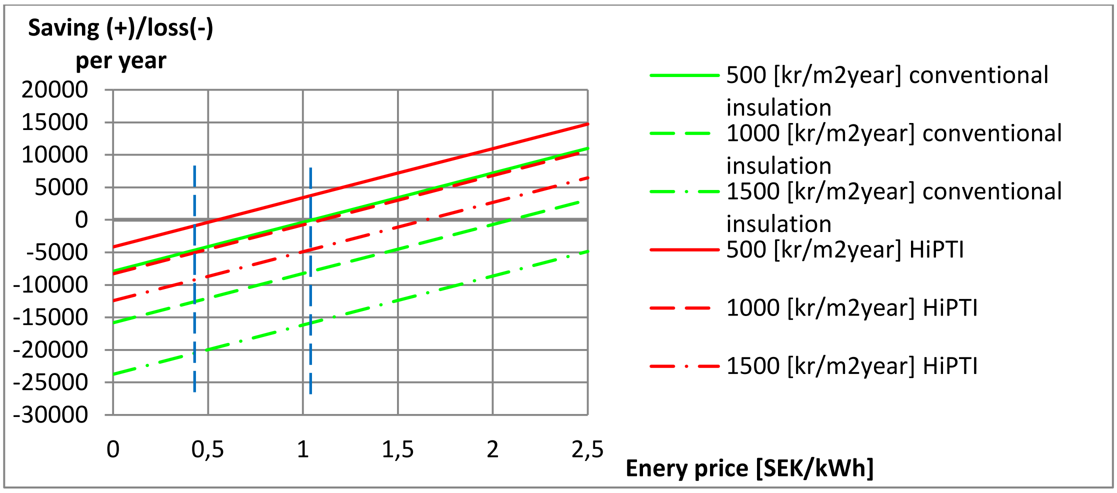

Figure 18. Balance between the savings due to energy efficiency and the losses due to decreased living area for different insulation and levels of rent. The calculation is made for the rents 500, 1000 and 1500 SEK/(m^2year) and for conventional as well as High Performance Thermal Insulation (HiPTI). The vertical dashed lines show the normal range of energy prices for heating in Sweden. Negative values means that the rent losses are greater than the energy savings.

Table 6. The input data used to evaluate whether it is profitable or not to insulate internally.

Total living area before	1080
Wall area	430 m^2
Existing insulation thickness in the wall	100 mm (λ=0.04 W/mK)
Conventional internal insulation	Insulation 50 mm (λ=0.04 W/mK) Gypsum board 13 mm Thermal resistance, R ≈ 1.25 K/W Total lost living area = 15.8 m^2
Internal insulation with HiPTI*	Insulation 20 mm (λ=0.016 W/mK) Gypsum board 13mm Gives thermal resistance, R ≈ 1.25 K/W Total lost living area = 8.3 m^2
Energy saving due to internal insulation	7 kWh/m^2/yr (according to the steady state model, se appendix 1)
**High Performance Thermal Insulation*	

For low rents and high energy prices, internal insulation is a profitable option, especially when using high performance insulation, but today this is seldom the case.

Internal insulation need to have more advantages than to decrease the transmission losses to be an attractive option to the owners. One possible advantage is decreased air leakage. The relation between leakage through joints and leakage through degenerated vapor barriers is not known. If air leaks through holes in the vapor barrier, energy might be saved by tightening the whole wall and not just the joints. The internal insulation could function both as a thermal insulator and a leakage blocker, which makes the option more interesting. In order to assess the benefits of such solution, an investigation should be done of how much the leakage can be improved by sealing joint leakages compared to tightening the whole face of the wall.

6.5 External insulation

External insulation is considered as the best additional insulation alternative due to moisture safety and reduction of thermal bridges. One way is to apply it directly on the existing façade, another to partly or completely demolish the existing wall and then apply the new insulation. Problems that can occur are that the new wall becomes too heavy or to thick and that the window recess gets to deep. There are also worries about moisture problems for certain solutions. All these potential problems must be evaluated and solved before the measures are done.

Sometimes building owners prefer solutions that allow the residents to stay in their apartments during renovation. This might affect the choice of external insulation method. A solution that only affects the outside of the wall can be preferable.

Insulation immediately on the old brick façade will be the cheapest option in terms of investment cost. In order to make the new insulation efficient the old ventilated air gap needs to be sealed. This can be done with blown mineral fiber insulation.

Another option is to demolish the existing brick façade, put new insulation on the underlying layer and then build a new façade. It could be beneficial to do this if the old façade is damaged or if the wall would get too heavy or too thick otherwise. In both the case with partial and no demolition it is important to consider the existing air tight layer. If material which is not permeable enough is put on the outside, there is a risk that moisture will be trapped between two tight layers with possible accumulation of moisture and microbiological growth as result. A possibility when demolishing the existing façade is to increase the air tightness by putting a new air tight barrier outside the existing infill wall. If the external insulation layer is thick enough and windows are placed far enough out in the construction, there would not have to be moisture problems, but organic material between two tight layers must be considered a risk construction.

The third alternative is to demolish the whole infill wall and rebuild it. This alternative has potential to increase the rentable space and makes an installation layer possible. An installation layer is good for the air tightness since the air tight layer is put about 50-70 mm into the wall which will prevent penetrations of it. A problem with this alternative is that much work needs to be done inside the apartment. Floor and wall claddings and radiators might need adjustment, replacement or removal. This solution is the one performed in Brogården. It might be the only one that can fulfill the demands for a very energy efficient house, but it will also become expensive and will therefore not suit every owner.

Condensation of water on the façade can be a problem for well insulated walls and might cause biological growth. This happens because modern paint is less toxic and because the wall face gets colder from clear sky radiation when the heat flow from the inside decreases and the façade becomes lighter and consequently less heat is stored in the outer wall and will be consumed faster. Dusty areas suffer worse than clean, rough surfaces worse than smooth and bright surfaces worse than the dark. (Håkansson 2007).

High performance thermal insulation (HiPTI) can be an alternative when there are restrictive requirements on the thickness or weight of the wall. The two most commonly discussed types of HiPTH are vacuum insulation panels (VIP) and aerogel blankets. Typical λ-values are 0.005 for VIP and 0.014 for aerogel blankets compared to about 0.033-0.037 for normal insulation materials. A disadvantage is that they are expensive.

Since the tightness of the old air tight layer was not known, it is difficult to say whether it is important to replace it or not. Further investigations must be done in order to say something general about this.

6.6 Thermal bridges

The worst thermal bridges are assumed and calculated in Heat 2 according to EN ISO 10211:2007 for different additional insulation thicknesses, $t_{tot}=t_1+t_2+t_3$ (see the drawings in appendix 5 or chapter 7.1), different degree of demolition and different window alternatives. The calculated Ψ-values can be found in appendix 4. The grid of the elements in the numerical calculation was refined until the third value digit in the result is not changed anymore. The results are presented in Figure 19. It shows the sum of all thermal bridges in the house for the different considered combination of measures. The input data for the energy calculations was taken from this chart.

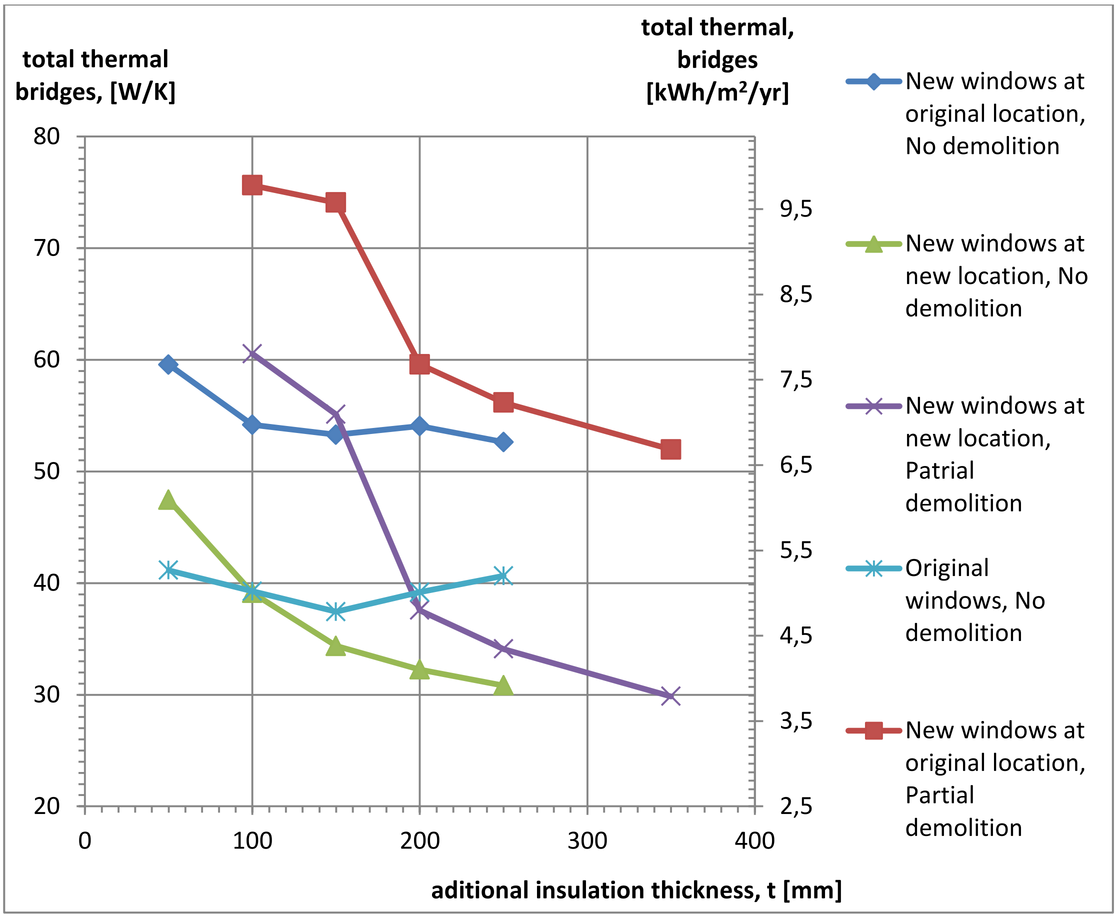

Figure 19. The sum of all thermal bridges for varying insulation thicknesses and the different renovation cases described in chapter 7.1. The energy consumption per square meter is based on the reference building and a mean annual temperature difference of 15K.

The graphs in the figure look rather different and a conclusion is that the window and wall combination has great influence on the total loss through thermal bridges. This is mainly because the window perimeter is large compared to the other thermal bridges. Another important bridge that can be noticed in the graph is the beam foundation insulation. Its effect is most obvious for the case of partial demolition and can be seen as a greater slope when beam foundation insulation is introduced between t=150 and t=200.

Values of the total thermal bridge losses vary between 20 and 80 W/K for the house in this work. The importance of bridges can be better understood by looking at Table 7 that display losses calculated in the steady state model. It can be seen from the table that thermal bridge losses represent a quiet small part of the total losses.

Table 7. Conductance and percentage of losses for different building parts in the original and pilot building calculated with the steady state model.

	Original		Pilot renovation	
	[W/K]	[%]	[W/K]	[%]
Thermal bridges	79	6	20	4
Walls	182	14	50	10
Windows and doors	407	31	203	42
Intended ventilation	456	35	91	19
Total*	1314	100	480	100
* Walls, windows, doors, roof, ground, thermal bridges, and intended ventilation				

An evaluation of window thermal bridge insulation (see Figure 20) was made based on energy savings calculated in Heat2 and LCC analysis based on (Janson, Berggren & Sundqvist 2008). The measure was found to be uneconomic compared to other options and is not considered in the following evaluation. It could however be a measure worth attention if the aim is a particularly energy efficient house.

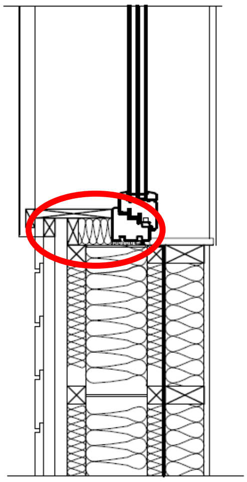

Figure 20. An example of window thermal bridge insulation, which is not handled in this work since it was estimated to be economically uninteresting. (Figure source: Ekstrands)

6.7 Façade solution

Only one façade solution was studied, ventilated façade board. Other common solutions that would be interesting to study are mineral and acrylic rendering on insulation. Mineral render allows the construction to breath and is usually put on mineral wool. Acrylic render is moisture tight but driving rain can get in through cracks causing accumulation of moisture in the construction. It is usually applied on cellular plastic and the method was popular because it was cheap and easy to mount, but it has been questioned because of its moisture risks. An alternative for acrylic rendering is to put it on mineral wool.

6.8 Chosen combinations

Based on the pre-study the following combinations are chosen for further detailed investigations.

- Original building with improved air tightness and heat recovery.
- Different insulation thicknesses and degree of demolition, new windows and improved air tightness.
- Different insulation thicknesses and degree of demolition, new windows, improved air tightness, heat recovery on ventilation and attic insulation.
- Different insulation thicknesses and degree of demolition, new windows, improved air tightness, heat recovery on ventilation, attic insulation and ground insulation.

See chapter 7 and appendix 8 for more detailed information about each combination.

Based on earlier investigations extensive energy efficiency renovations like the one in Brogården are not economically viable. The attempt was therefore to find combinations with better profitability. The idea was that options with less intervention in the original building are more profitable.

7 Input data for calculations

Calculations are carried out for different combinations of renovation measures as described in the previous chapter. The wall renovation measures can in turn be divided into four cases. For each case the insulation thickness varies. The four cases are:

- Original wall
- Additional insulation with no wall demolition
- Additional insulation with partial wall demolition
- Pilot. Total demolition and reconstruction of walls (except for load bearing parts)

7.1 Wall types

The external walls in the reference building were idealized as two types, infill walls and load bearing walls. The load bearing walls are located at the short sides of the building and the infill walls on the long sides. The calculations are based on the four cases with variations of additional insulation thickness and window placement.

7.1.1 Original

The original walls are modeled after the drawings in Figure 21

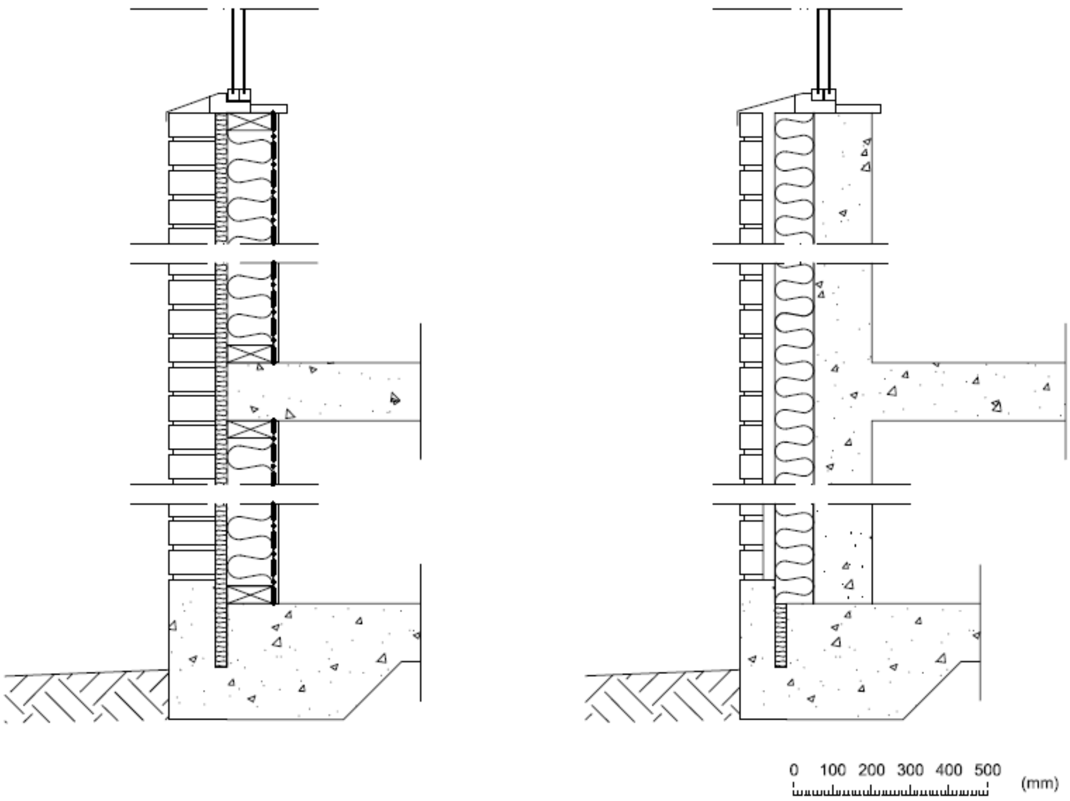

Figure 21. Infill and load bearing wall from the original building in Brogården.

7.1.2 Additional insulation, no demolition

The most economical way to insulate additionally (in terms of investment cost) is to put the insulation directly on the original facade. This will also stop the frost damages in the bricks because of temperature raise and drying out. The insulation layers 1 and 2 include façade-bearing metal studs in them. Layer 3 is an unbroken insulation layer. There are two alternatives for windows. Either the original or already mounted new windows are left on the old location (alternative 2) or new ones are mounted at an optimum location that decreases the thermal bridge to a minimum (alternative 1).

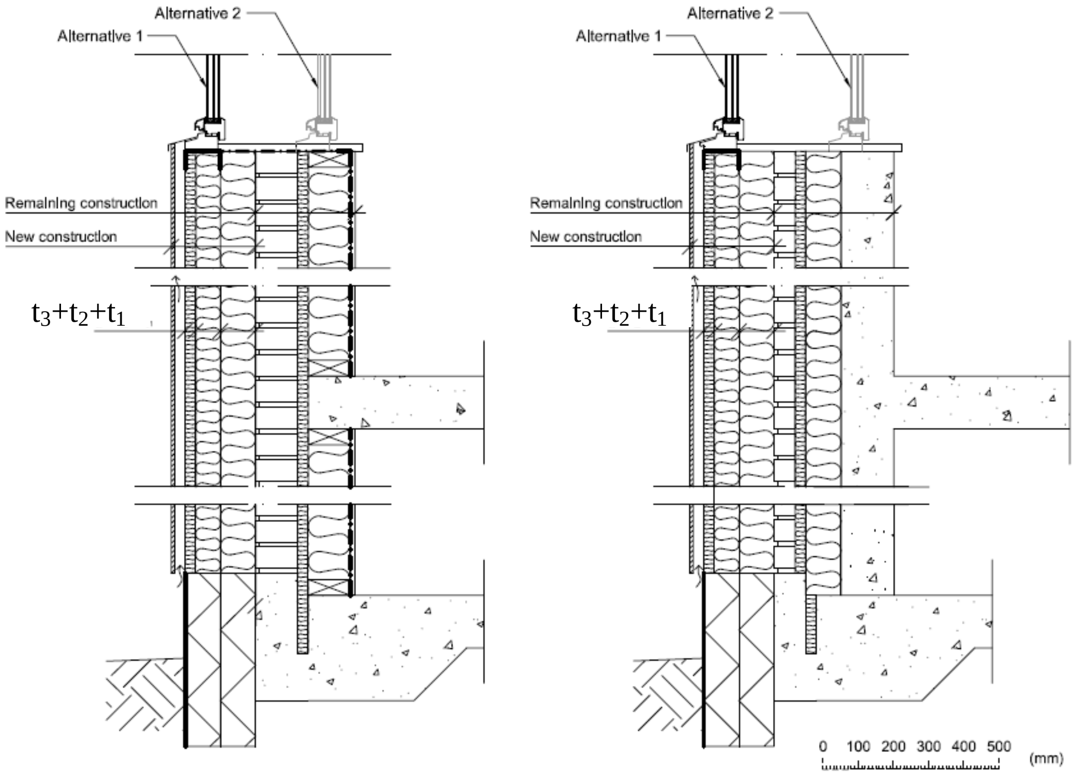

Figure 22. Infill and load bearing wall. Additional insulation, no demolition.

7.1.3 Additional insulation, partial demolition

If the brick facade is in very bad shape it might be preferable to demolish it as can be seen in Figure 23. This will also keep the wall thickness down compared to the same additional insulation thickness in the case of no demolition. This alternative also makes it possible to replace the old insulation, whose performance may have decreased, with new.

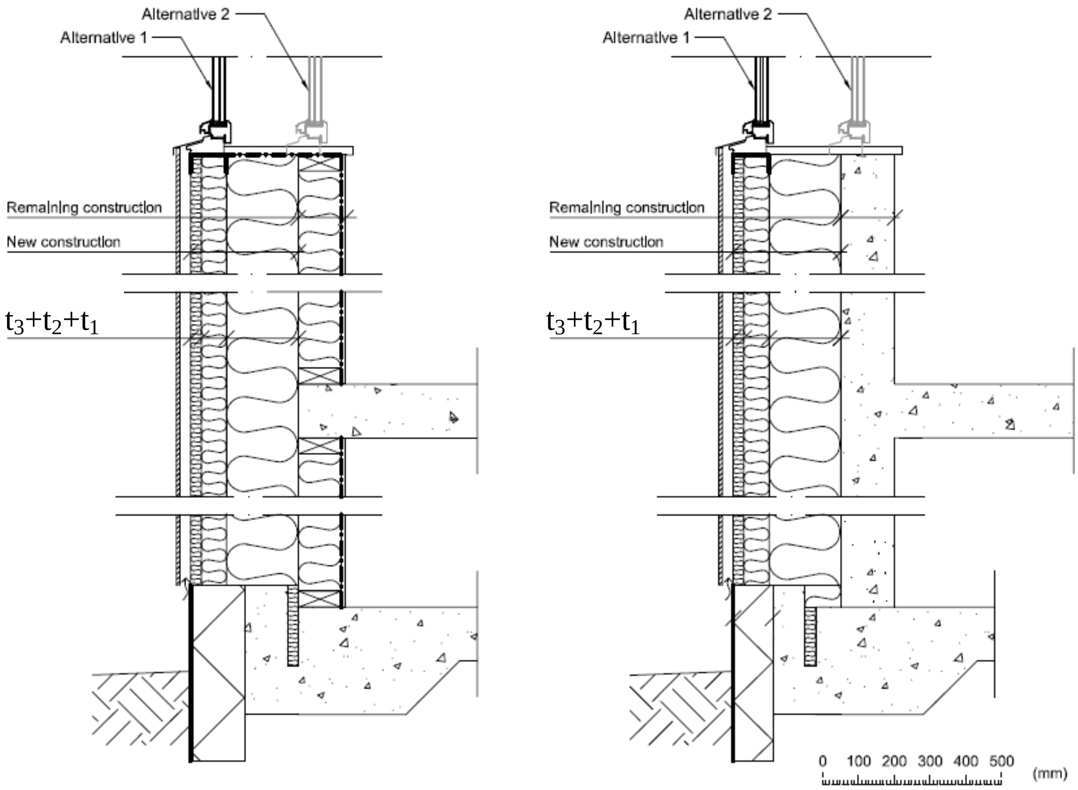

Figure 23. Infill and load bearing wall. Additional insulation, partial demolition.

7.1.4 Pilot renovation - additional insulation, full demolition

In the pilot renovation the infill walls were completely removed and only the load bearing concrete in the short end walls were remained. This made it possible to ensure good air tightness, the indoor area was increased slightly due to the new thinner wooden stud wall and an installation layer could be built.

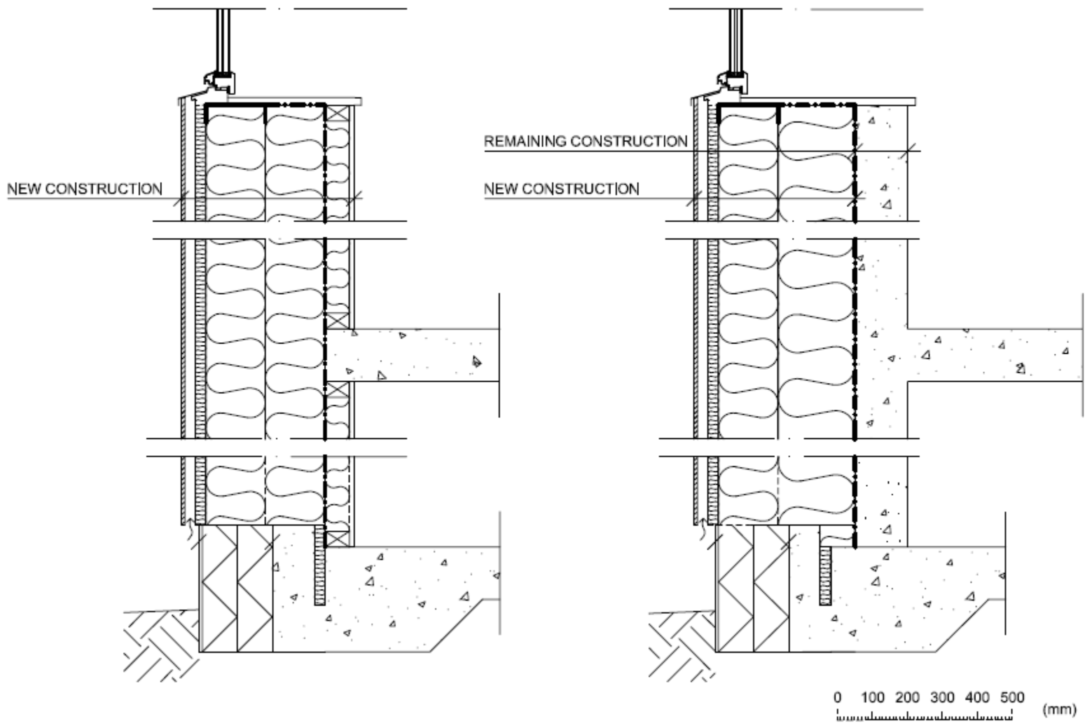

Figure 24. Infill and load bearing wall in the pilot renovation: Additional insulation, full demolition.

7.1.5 Wall insulation thicknesses used in the calculations

The thickness of the facade bearing insulation layer, t_2+t_3, (see Figure 22 and Figure 23) is set to the same as in the pilot renovation which is 170+30 mm. When the additional insulation is less than 200 mm t_2 is reduced and when it is greater an unbroken layer t_1 is used. (See the figures in 7.1.1 - 7.1.4) The thicknesses are chosen to give mean U-values of approximately 0.1, 0.15 and 0.2. Table 8 shows the chosen insulation thicknesses.

The alternatives are given names with a letter usually followed by a number. P=pilot, H=High aims, I=intermediate aims, L=Low aims, O=Original 1=No demolition, 2=Partial demolition and 3=Internal insulation.

Table 8. Wall insulation thickness for the different alternatives in the calculations.

	Infill wall [mm]				**Load bearing wall** [mm]				**Beam foundation** [mm]	**U-value** [W/(m²·K)]
	t_1	t_2	t_3	t_{tot}*	t_1	t_2	t_3	t_{tot}*	t_{gi}**	U_{mean}***
High aims U≈0.10										
P: Pilot	-	-	-	492	-	-	-	647	200/200	**0.104**
H1: No demolition	100	170	30	635	100	170	30	692	300/300	**0.104**
H2: Partial demolition	100	170	30	485	200	170	30	552	150/210	**0.110**
Intermediate aims U≈0.15										
I1: No demolition	0	170	30	535	0	170	30	592	200/200	**0.140**
I2: Partial demolition	0	170	30	385	100	170	30	502	50/110	**0.152**
Low aims U≈0.20										
L1: No demolition	0	40	30	405	0	40	30	462	70/70	**0.210**
L2: Partial demolition	0	70	30	285	0	170	30	402	0/10	**0.220**
L3: Internal insulation	70****			366	70****			423		**0.197**
Original										
O: Original	-	-	-	283	-	-	-	340		**0.309**

* Total wall thickness
** t_{gi}=Thickness of beam foundation insulation
***Mean area weighted value for the two wall types. Calculated with thermal conductivities according to Table 14
**** Internal insulation thickness

7.2 Windows

The original windows were coupled 2-pane with wooden frames. The new ones are 3-pane with argon filling. The characteristics in
Table 9 are assumed for the steady state and thermal bridge calculations.

Table 9. Window characteristics used in steady state and transient heat and energy calculations.

	U_{frame} [W/(m²K)]	U_{glass} [W/(m²K)]	A_{frame}/A_{window} [m²]	Ψ_{spacer} [W/(m·K)]	$\Psi_{installed}$ [W/(m·K)]
Original*	1.7	3	0.1	0	***
New**	1.1	0.5	0.1	0.027	***

* Calculated according to EN ISO 10077-1-2006 with d_1=105, d_2= d_3=29
** Values from (Ekstrand 2011).
*** According to Heat2 calculations. The results differ for each wall construction. See appendix 3

The calculation tool IDA needs supplementary input parameters for windows. The main difference is that parameters for insolation are added. They are set according to Table 10. There was no separate input for the windows' thermal bridges. Instead a total value for thermal bridges is stated for each zone. Hence, values are needed for the thermal bridge caused by the window pane spacer, Ψ_{spacer} and the bridge caused by boundary effects, $\Psi_{installed}$, so that they can be added to the total bridge for the zone.

Table 10. Additional window characteristics used in the IDA energy calculations.

	Solar heat gain coefficient SHGC [-]	**Solar transmittance** [-]	**Internal emissivity** [-]	**External emissivity** [-]
Original	0.76	0.68	0.9	0.9
New	0.69	0.58	0.9	0.9

Different placement of windows will affect the size of thermal bridges and depth of recesses which in turn will affect the insolation. Thermal bridges were evaluated for combinations of original and new windows and original and optimal placement in the wall construction (see chapter 7.1).

7.3 Ground insulation

The same ground insulation method as in the pilot renovation is used for all cases where ground insulation is added. The original "floating" floor on the ground concrete slab is replaced with chipboards on efficient insulation according to Table 11.

Table 11. Material layers in the ground construction.

	Original	**New (Pilot and calculated renovations)**
Replaced	Floor cladding	Floor cladding
	50 Concrete	Chipboard
	60 Sand	-
	30 Mineral wool	80 Insulation λ=0,023 W/(m·K)
Remaining	180 Concrete	180 Concrete

7.4 Roof insulation

The original roof insulation is 180 mm mineral wool on the roof slab. When additional insulation is applied the total thickness is extended to 420 mm.

7.5 Building geometry

Calculations was made for a building geometry based on the original design, see Figure 25. It consists of three zones, one for each floor. For the 2nd and 3rd storey the entrance doors are replaced with windows. The simplification was done in order to make the IDA model easier to handle: each story (or zone in the IDA model) was seen as a rectangular box instead of the real design with inset balconies. The thermal bridges however were calculated according to the real design. Because of the simplification the modeled wall area became 16.2 m^2 smaller than the real area, which was compensated for by increasing the thermal bridge conductance. As a consequence of this simplification, the thermal inertia and radiation effects for 16.2 m^2 exterior wall was neglected. This happens because the thermal bridges are modeled as just a conductance, instead of the physically more sophisticated wall element model.

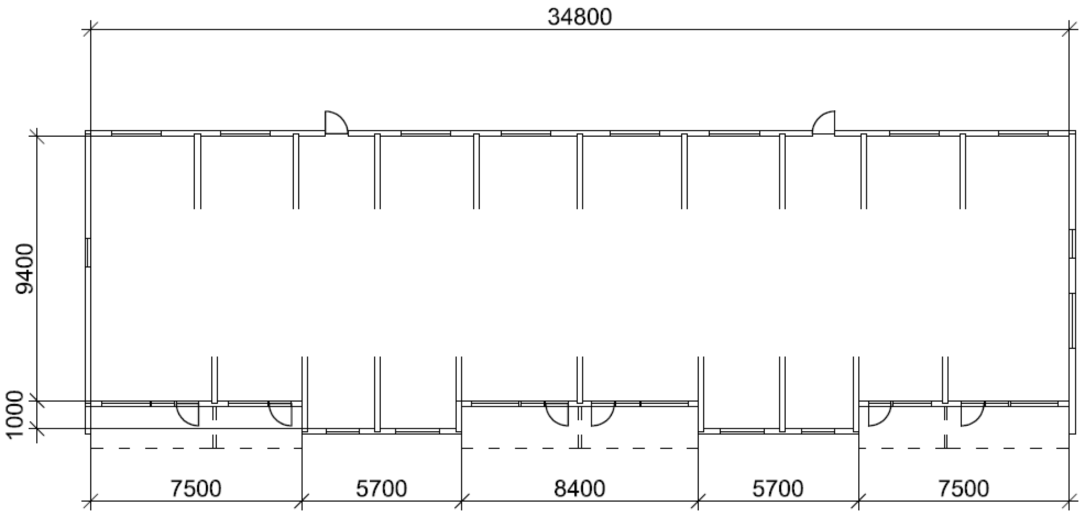

Figure 25. Plan of the reference building from which the model was created.

The buildings model has lengths and areas according to Table 12.

Table 12. Geometry and lengths of thermal bridges in the model of the reference building.

Geometry		**Thermal bridges**	
Lengths	[m]	*Lengths*	[m]
Length	34.8	Balcony	82.2
Width	10.4	Internal slab	139.2
Height (to roof slab)	8.1	Interior wall	113.4
Areas	[m^2]	Vertical wall-wall	64.8
Windows	160.0	Window/door perimeter	444.0
Doors	43.3	Beam foundation	
Infill walls	367.7	Roof-Wall	
Concrete walls	177.4		
Ground slab	361.9		
Roof slab	361.9		
Internal concrete walls (one side)	759.0		

7.6 Thermal bridges

Thermal bridges are considered as a total conductance (W/K) for each zone. An estimation was done of which the worst thermal bridges are. The following thermal bridges were calculated in Heat2 and used in IDA:

- Vertical corner: infill wall – concrete wall
- Interior load bearing wall
- Internal slab
- Balcony
- Window and door perimeter.
- Beam foundation
- Corner: roof – exterior wall

Figure 26 shows how the thermal bridges are distributed. Their lengths are presented in Table 12.

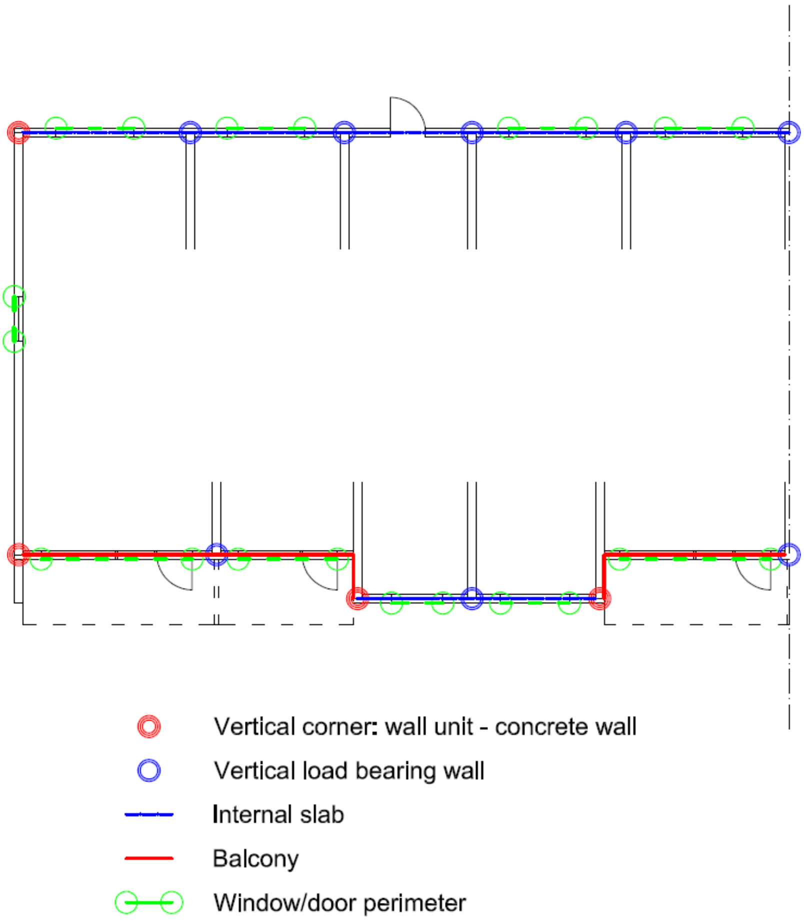

Figure 26. Thermal bridges considered in the model of the reference building. (The beam foundation and roof-wall corner is not shown in the figure, but is considered in the model)

All the previously described thermal bridges occur in joints where elements meet, but there are also bridges inside elements, caused by such as studs and wall ties. These were considered by setting a higher thermal conductivity (λ-value) for the layer where the thermal bridges were. See the chapter 0 for more information.

7.7 Air exchange

The original building has mechanical exhaust ventilation whereas the calculated renovations as well as the pilot renovation have balanced ventilation. Input data for the two systems are presented in
Table 13. Air is allowed to move freely between the zones (storeys) by introducing big leakages in the internal slabs in the IDA model. This has effects on the pressure distribution over the external walls and in turn the leakage through them.

Table 13. Ventilation system input data.

	Mechanical exhaust ventilation	**Balanced ventilation**
Exhaust air flow [$l/(s \cdot m^2)$]	0.35	0.35
Venthole power law constant [$m^3/(s \cdot Pa^n)$]	0.115	-
Leakage power law constant [$m^3/(s \cdot Pa^n)$]*	0.232 – 0.035*	0.232 – 0.035*
Power law exponent, n [-]	0.65	0.65
Persily-Kronvall estimation model constant, c	25	25
Exhaust fan pressure rise, ΔP [Pa]	400	500
Supply fan pressure rise ΔP [Pa]	-	800
Fan efficiencies, η [-]	0.6	0.6
Desired supply air temperature [°C]	-	17
Heat exchanger efficiency, η [-]	-	0.6-0.8
* corresponding to air tightness's $2 < q_{50} < 0.3$		

7.8 Material properties

The energy and heat and moisture calculations were based on the material data in Table 14.

Table 14. Material data used in the energy and heat and moisture calculations.

	Density [kg/m^3]	**Porosity** [m^3/m^3]	**Heat Capacity** [J/(kg·K)]	**Thermal Conductivity** [W/(m·K)]	**Diffusion resistance factor** [-]	**Sd-value** [m]
Mineral wool	60	0.95	850	0.04	1.3	-
Broken mineral wool*	-	0.95	850	0.05	1.3	-
XPS	40	0.95	1500	0.03	100	-
EPS	15	0.95	1500	0.04	30	-
Gypsum board	850	0.65	850	0.2	8.3	-
Brick masonry	1650	0.41	850	0.6	9.5	-
Brick tiles**	1900	0.24	850	0.6	10	-
Mineral render	1900	0.24	850	0.8	25	-
Acrylic render	1100	0.12	850	0.14	1000	-
Foil on gypsum board	-	-	-	-	-	1500
* Mineral wool + wooden studs, metal studs or wall ties ** The 22 mm thick brick tile façade used in Brogården pilot						

7.9 Energy consumption boundary and initial conditions

Many factors apart from the building characteristics influence the energy consumption such as climate and residents' behavior. The energy calculations are based on the input data in Table 15.

Table 15. Chosen input data influencing the energy consumption.

Indoor air temperature	22 °C
Window airing	no
Solar shading	no
Climate data	Säve -77 (with T_{mean}=7,19°C)
Wind profile	Urban area (A_{coeff}=0.67 A_{exp}=0.25)
Hot water flow based on (Warfvinge 2008) and measured data from Brogården (T_{tap}=55, T_{in}=5)	0.0247 l/s (1) 0.0159 l/s (2) 0.0106 l/s (3)
Household electricity	4.45 W/m^2 (4) 3.20 W/m^2 (5)
(1) corresponds to 42 kWh/m^2/yr (original consumption) (2) corresponds to 27 kWh/m^2/yr (with water saving nozzles) (3) corresponds to 18 kWh/m^2/yr (whole new system as in the pilot renovation) (4) corresponds to 39 kWh/m^2/yr (original consumption) (5) corresponds to 28 kWh/m^2/yr (consumption after installing efficient equipment)	

7.10 Moisture transfer

The moisture condition in the building elements is influenced by other factors than outdoor climate and material characteristics such as indoor moisture production and leakages. The following conditions were used in the moisture transfer calculations:

- Indoor moisture supply, $\Delta v = 3$ [g/m^3]
- Leakage from the outside: 1% of driving rain entering at the depth of the window frame front.
- Leakage from inside: Not considered.
- Air exchange rate in air gap:

The climate file used in the WUFI calculations was created by the computer software Meteonorm for the location Säve outside Gothenburg.

7.11 Life cycle cost

Input data for the LCC-analysis was based on two previous investigations. Janson, Berggren & Sundqvist (2008) has made a cost and energy investigation similar to the one in this work. The investment costs used in this work was based on their figures. Gerdin & Hammarberg (2010) focus more on economic conditions and they tried to answer why energy efficient renovations are so seldom performed today. They have chosen slightly different input data which gave big differences when comparing the results. The input data is shown in Table 16.

Table 16. Input data for the LCC calculation made by Janson, Berggren & Sundqvist (2008) and Gerdin &.Hammarberg (2010)

Parameter	unit	J, B & S (2008)	G & H (2010)
Electricity price	SEK/kWh	0.90 SEK	1.00 SEK
District heating price	SEK/kWh	0.50 SEK	1.00 SEK
Electricity price increase/year	-	5.00%	5.00%
District heating price increase/year	-	3.00%	5.00%
Nominal interest rate	-	8.00%	6.00%
Monetary inflation	-	4.00%	2.00%
Real interest rate	-	3.80%	3.92%

The investment costs used for this works renovation alternatives was evaluated by linear interpolation when (Janson, Berggren & Sundqvist 2008) did not have the exact values. In some cases reasonable assumptions provided the basis for the investment cost. (See appendix 5 for the used numbers on investment cost.)

7.12 Combinations of measures in the energy calculations

In the energy calculation the wall renovation alternatives described earlier in this chapter (7.1.5) was combined with renovation alternatives for other building elements. The combinations and their designation are presented in Table 17. The different combinations were divided into five categories:

1. The original and pilot renovation (1a and 1c). 1b is the original building with façade renovation, i.e. no energy improving measures.
2. Measures related to air tightness. The purpose of this category was to find the energy reducing potential of air tightening as a single wall renovation measure.

3. Wall renovation, change of windows and air tightening. The air tightness is set to q_{50}=0.6 which is an assumed possible tightness when only sealing joints. The same tightness applies for category 4. The purpose was to find if this is a possible alternative to façade renovation and also to compare a change of windows with a change of windows and additional wall insulation.
4. Wall renovation, air tightening, new windows, balanced ventilation system with heat recovery and additional insulation on the roof. With this category an attempt was made to find an alternative to the pilot renovation. By reducing the intervention in the original design the hope was to find an energy efficient solution that was more cost efficient than the pilot renovation.
5. Compared to category 4 this is supplemented with better air tightness (q_{50}=0.3) and ground insulation. It is interesting to see how much better the results will be if this air tightness could be achieved. The expectations were that this combination would be cost effective.

Table 17. Combinations of measures in calculations

	Wall*	Tight. (q_{50})	Windows	Vent.	Roof	Ground	HW red	HE red
1a	O	2.0	O	ME	O	O	No	No
1b	O	2.0	O	ME	O	O	No	No
1c	P	0,3	New	B, η=0,8	New	New	High	Yes
2a	O	2.0	O	ME+HP	O	O	No	No
2b	O	2.0	O	B, η=0,6	O	O	No	No
2c	O	2.0	O	B, η=0,8	O	O	No	No
2d	O	1.0	O	B, η=0,8	O	O	No	No
2e	O	0.6	O	B, η=0,8	O	O	No	No
2f	O	0.3	O	B, η=0,8	O	O	No	No
3a	O	0.6	New	ME	O	O	No	No
3b	L1	0.6	New	ME	O	O	No	No
3c	I1	0.6	New	ME	O	O	No	No
3d	H1	0.6	New	ME	O	O	No	No
3e	I2	0.6	New	ME	O	O	No	No
3f	H2	0.6	New	ME	O	O	No	No
4a	O	0.6	New	B, η=0,8	New	O	Yes	Yes
4b	L1	0.6	New	B, η=0,8	New	O	Yes	Yes
4c	I1	0.6	New	B, η=0,8	New	O	Yes	Yes
4d	H1	0.6	New	B, η=0,8	New	O	Yes	Yes
4e	I2	0.6	New	B, η=0,8	New	O	Yes	Yes
4f	H2	0.6	New	B, η=0,8	New	O	Yes	Yes
5a	O	0.3	New	B, η=0,8	New	New	Yes	Yes
5b	L1	0.3	New	B, η=0,8	New	New	Yes	Yes
5c	I1	0.3	New	B, η=0,8	New	New	Yes	Yes
5d	H1	0.3	New	B, η=0,8	New	New	Yes	Yes
5e	I2	0.3	New	B, η=0,8	New	New	Yes	Yes
5f	H2	0.3	New	B, η=0,8	New	New	Yes	Yes
ME: Mechanical Exhaust B: Balanced HP: Heat Pump HW: Hot Water HE: Household electricity red: reduction * Wall types according to chapter 7.1.5: P=pilot, H=High aims, I=intermediate aims, L=Low aims, O=Original 1=No demolition, 2=Partial demolition								

8 Calculation results

8.1 Energy consumption

The calculations show that the energy goals can be reached with less extensive renovation than the one in the reference building.

There were problems with the verification of the energy models due to lack of data, but the results are reasonable and a comparison between the modeled energy consumptions for the different alternatives still makes sense.

8.1.1 Verification of calculations and evaluation of the models

The idea was to verify the energy calculations by comparing them to measured data. For the original design the only available data was mean values from the whole housing estate which means that the comparison with the single modeled house J becomes unreliable. The data from after the renovation was also not from house J, which makes this comparison unreliable too. The results are presented in Figure 27.

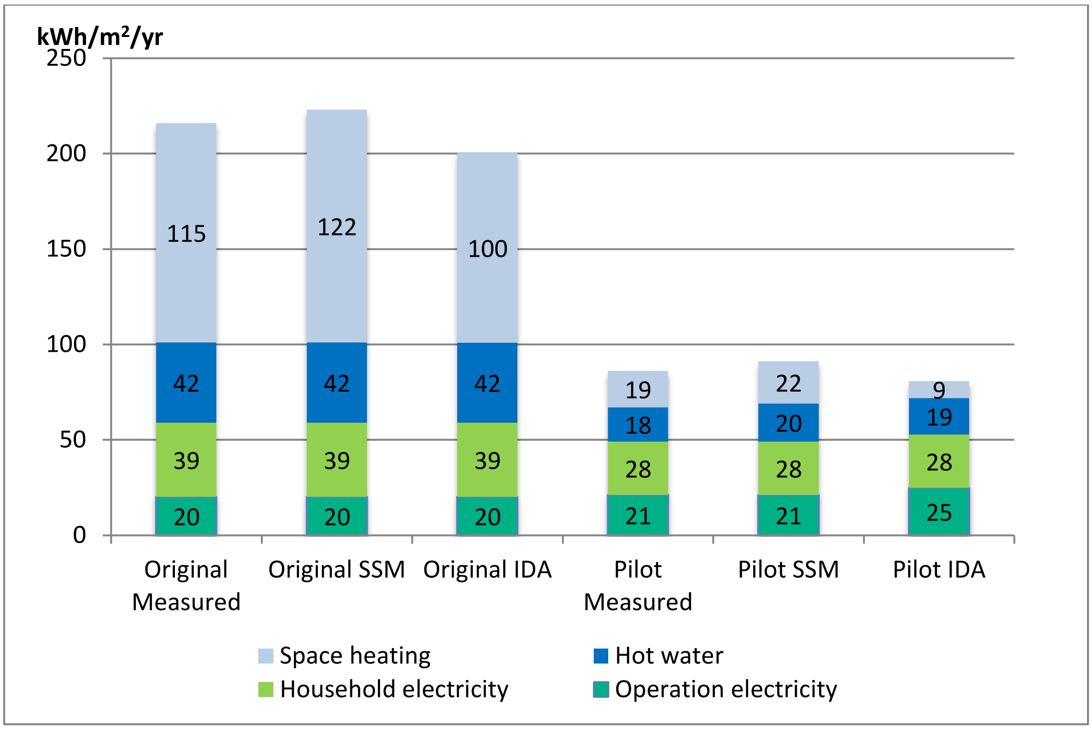

Figure 27. Comparison between measured energy consumptions and consumption calculated with the Steady state model (SSM) and IDA, for the original building and the pilot renovation.

It is still possible to draw some conclusions from these calculation results, even though the verification cannot be done. It seems like the steady state model (SSM) overestimates the energy consumption and like the IDA model underestimates it. To some extent this depends on air exchange. The steady state model uses the Persily-Kronvall estimation model with the constant c=25 [-] and IDA uses the power law together with wind, stack and fan pressure. As a consequence the air leakage will differ for the two models. For the original building the heat losses due to air leakage becomes the following:

- SSM: 12.7 kWh/m^2/yr
- IDA: 1.6 kWh/m^2/yr

The total energy consumption from the steady state model and IDA differs with 22 $kWh/m^2/yr$ for the original building as can be seen in Figure 27. Hence, approximately half of the difference can be explained by how the air tightness is calculated.

Window airing was not considered in any of the models. This can be a reason why the IDA model gives low consumption. Another reason could be that there are more thermal bridges that should have been considered.

Further, the operation electricity energy consumption calculated by IDA is too high for the pilot case. A balanced ventilation system requires more energy than a mechanical exhaust system so the consumption should increase, but the difference in reality is less than the one calculated in IDA. The measurements indicates an increase from 20 to 21 $kWh/m^2/yr$ when renovating but the calculations give an increase from 20 to 25 $kWh/m^2/yr$. A reason could be that the original system is not adjusted and therefore less energy efficient in reality than assumed in the calculations. The increase when comparing the badly tuned original heating and ventilation system to a new fine-tuned system could therefore be small as the measurements indicate. Assuming less efficiency in the original system would probably make the calculations more accurate.

8.1.2 Energy consumption of d renovation combinations

The results of the energy calculations made by IDA are presented in Figure 28. See appendix 8 for a description of each renovation alternative.

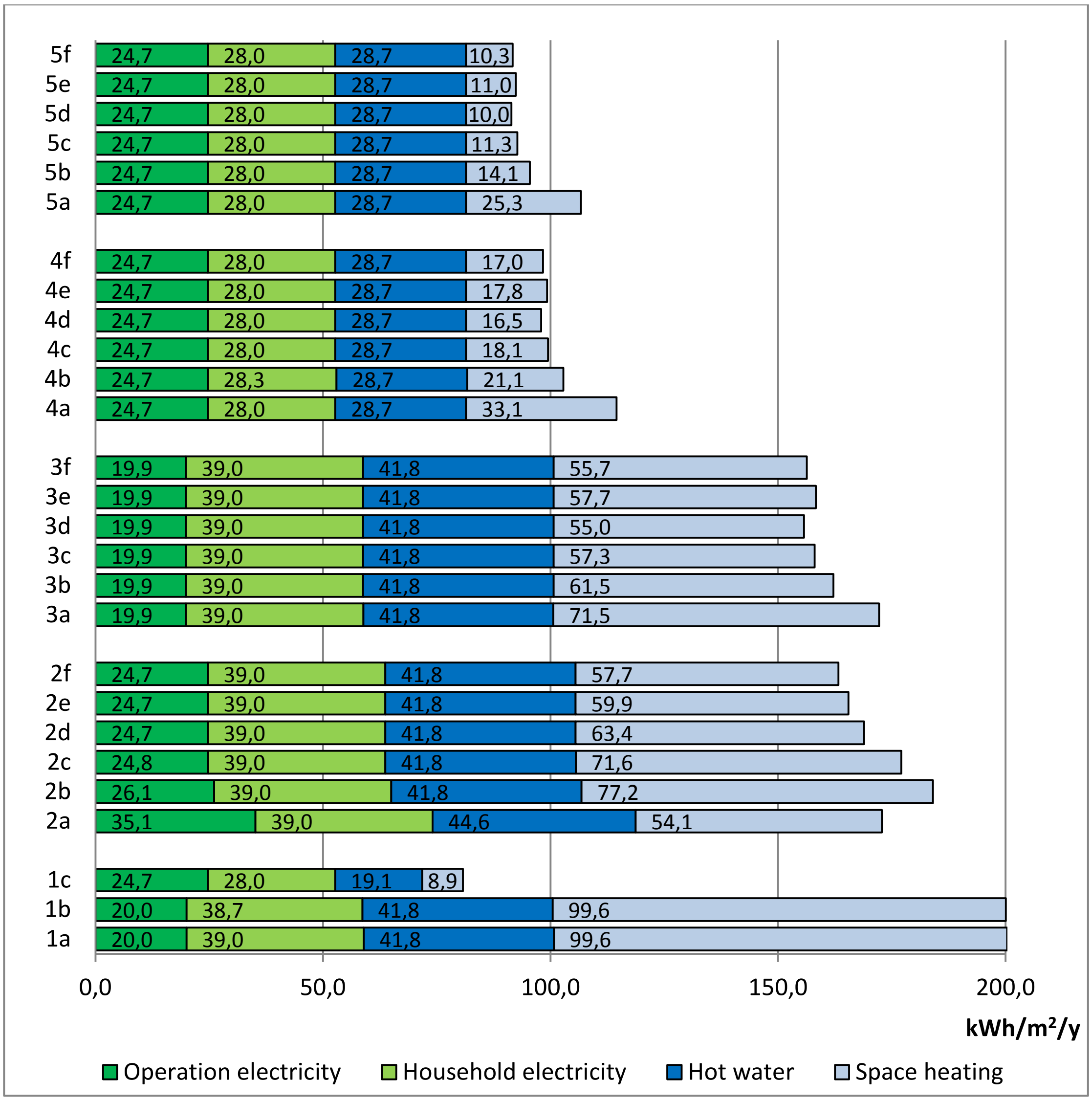

Figure 28. Results of the energy calculations.

Category 1 contains the original building and the pilot renovation. Category 2 includes different combinations of air tightening and ventilation heat recovery. For all categories the a-combination (1a, 2a etc.) has the original exterior walls, i.e. nothing is done with the walls.

The main purpose of Category 3 is to find out if it the chosen wall renovation solutions (3b-f) are cost effective compared to just repairing the damaged façade (1b). Alternative 3a shows the effect of air tightening and changing windows. 3b-f shows the effect of adding additional insulation. There is a small but significant effect on energy use of additional insulation compared to only air tightening and changing windows.

Category 4 shows the results of change of windows, air tightening, new ventilation system, additional insulation on roof and walls, water saving taps and efficient household equipment. A reduction of the energy consumption by 50% is possible with these measures.

Category 5 is an improvement of category 4. The air tightness is improved from q_{50}=0.6 to q_{50}=0.3 and ground insulation is added on the original slab. With these measures the space heating energy consumption gets close to the pilot renovation and the measures are still less extensive.

8.2 LCC

The LCC-analysis is based on input data from two sources, (Janson, Berggren & Sundqvist 2008) and (Gerdin & Hammarberg 2010). The varying input data give big differences in the results.

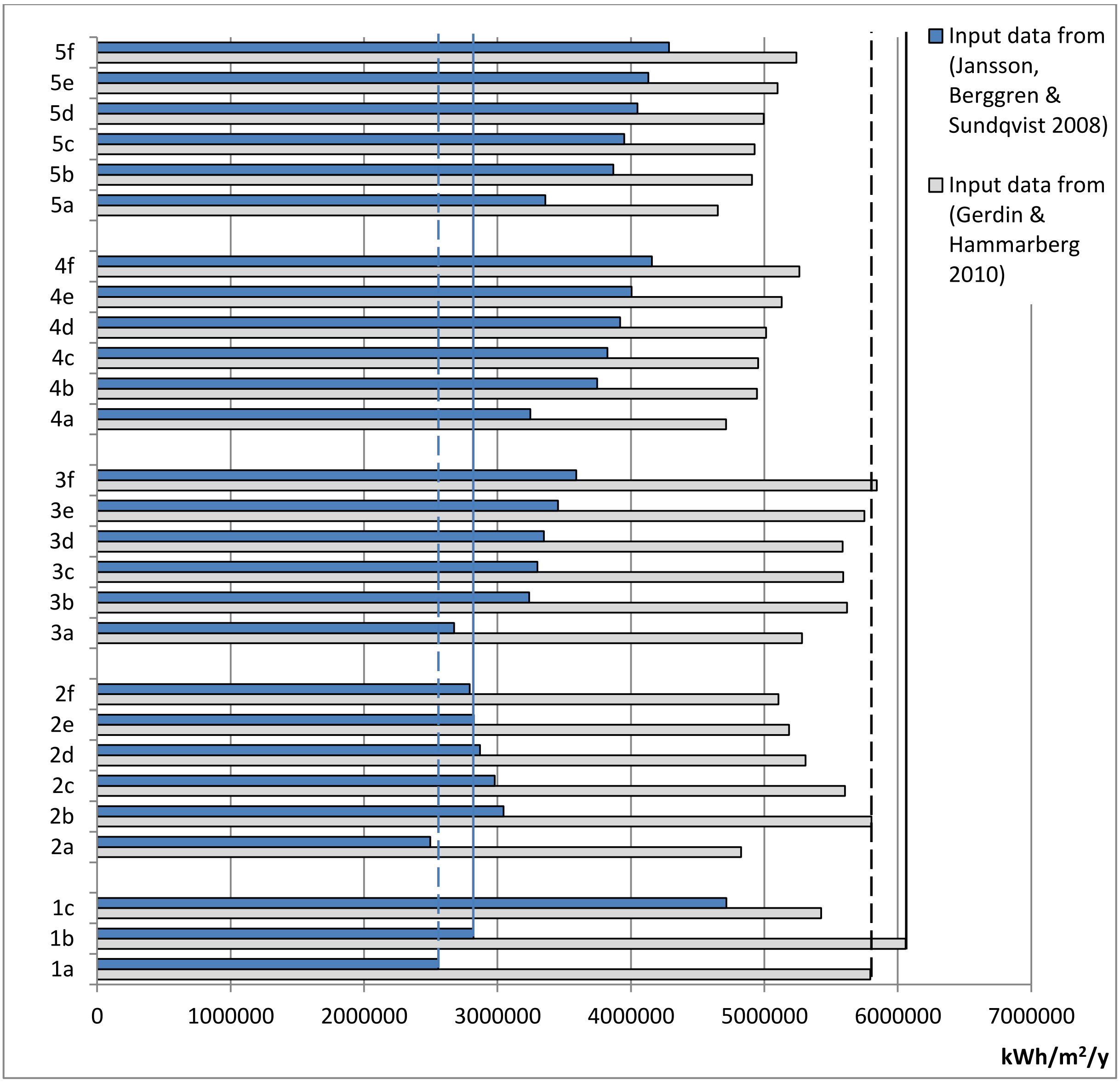

Figure 29. LCC 30 years with different input data.

There are vertical lines originating from the bars for the LCC of the original building (1a and 1b). 1a is the original building with no measures. 1b is the original building with repairs of the degenerated façade but no energy reducing measures. Alternatives that do not solve the problem with crumbling facades (2a-f, 3a, 4a, 5a) should be compared to 1a with the dashed help lines. The rest should be compared to 1b with the continuous lines.

8.3 Moisture safety

The additional insulation method with mineral wool and ventilated façade is a well proven solution and the calculations indicate no moisture problems.

The problem with frost damaged bricks can be perceived in the moisture calculations as high moisture content in the brick layer during winter. The wall renovation solution L1 with 70 mm additional insulation and ventilated façade solves the problem since the temperature never reaches below 0° degrees Celsius. The alternative to protect the bricks by just adding a new ventilated façade board was calculated and gave a reduction by half of the moisture content in the bricks which should also stop the decay due to frost damages.

8.4 Indoor comfort

The directed operative temperatures from the IDA calculations show no problem with radiant temperature asymmetry when carried out for a winter case and a summer case.

The worst comfort problem that has been found was over-temperatures during summer. This however is doubtful results, since window airing is not considered. Assuming that the residents opens the windows for cooling when the indoor air temperature rises above 27°C gives an outdoor temperature of 10.7°C when the windows are first opened in early spring. The cold outdoor air will enter and probably reach the residents before it is warmed up.

The floor temperatures 0.6 m from the inside of the exterior wall by the beam foundation has been calculated with a simplified steady state model according to (Petersson 2007). It gives a temperature range of 19.2-20.0°C for the different wall and ground insulation alternatives.

Problems with draught can be expected when cold air enters through the wall, either through ventholes or leakages. This problem decreases with better air tightness together with a balanced ventilation. If the mechanical exhaust air system is kept and much additional insulation is applied the consequence is that the heating period ends earlier and the inlet air entering behind the radiators will be colder when the radiators are turned off.

9 Conclusions

The evaluation shows that a perspective of 30-50 years is necessary to get economic viability of very energy-efficient renovations. It is however possible to reach the national energy goals with less extensive renovation than in the pilot renovation.

Comfort problems due to overheating can limit the suitable amount of additional insulation. The houses from the studied time period are not designed to keep the insolation down. Window areas in certain directions are disadvantageous. Since additional wall insulation is expensive it might be wise to consider limitations of this particular measure if overheating turns out to be a problem.

The hypothesis that the best renovation alternative can be found by studying the factors cost, energy efficiency, thermal indoor climate and heat and moisture condition in the wall is not disproved, but the factors could be evaluated differently.

9.1 Energy

It is possible to reach the energy goals of 50% reduction of energy consumption with less intervention in the original building than in the pilot renovation. It is interesting to note, that among the calculated alternatives it was only the ones with additional wall insulation that reaches the goals.

After taking the most cost effective energy reducing actions, less and less economic measures are left to carry out. Additional wall insulation can be considered one of these less economic measures which is performed to reach particularly low transmission losses. For the well-insulated alternatives the space heating was down at levels of less than half of the other posts.

The cost for increased insulation is assumed to increases linearly with the thickness. Heat losses on the other hand do not decrease linearly with increased insulation thickness. The energy improvement falls off when adding more and more insulation. This means that a doubled thickness will give the double cost but less than half reduction in energy consumption. Consequently, an optimal insulation thickness can be found for each building part based on investment cost and energy cost during the service life. Hence, it is not always economical with extensive additional wall insulation. In fact, just a small improvement of the U-value can be more economical under certain circumstances.

9.2 LCC

Additional external wall insulation could be advisable based on the LCC analysis depending on the choice of input data and calculation period. When adding insulation, demolition of the original façade is less profitable than keeping it even if it allows an air tightness improvement to q_{50}=0.3 instead of q_{50}=0.6. Investment costs and LCC input data should be investigated more carefully, but the results suggest that the two most economical options are:

1. External insulation without demolition of the original façade
2. Repairs and moisture protection of the original façade.

These two alternatives together with other energy improving measures are probably the most economical in the long run, which can also be seen in Figure 29 that presents the LCC for 30 years.

The large variation in life cycle cost because of the varying input data mainly depends on variations in the choice of energy price and energy price increase. With data from (Janson, Berggren & Sundqvist 2008) no alternative pays back within 30 years. It can also be noticed that the profitability decreases with thicker additional wall insulation and higher degree of wall demolition (look at the difference when going from alternative a to f in category 3-5). With data from (Gerdin & Hammarberg 2010) all alternatives pays back within 30 years and the most energy efficient ones have lower LCC. The same trend with less profitability for increased insulation thickness and degree of demolition can be seen (see appendix 7 for calculations with other life spans). Consider external wall insulation with no façade demolition, input data from (Gerdin & Hammarberg 2010) and taking into account the necessary repairs of the original facade. The breaking point where it becomes more profitable to perform additional insulation than not to is after about 30-50 years depending on what other measures are performed. Using (Janson, Berggren & Sundqvist 2008) gives a breaking point after 50 years.

9.3 Moisture safety

The studied renovation solutions was found moisture safe based on the WUFI calculations, but there are some special cases worth to note:

The somewhat peculiar solution for the original infill walls with 30 mm mineral wool instead of an air gap on the inside of the brick leaf might cause moisture problems. The outside edge of the wooden stud is exposed to relative humidities over 80% together with temperatures over 15°C during several months each year according to the calculations. This could result in mould problems. If air is allowed to move vertically through the 30 mm mineral wool layer or if the air leakage through the wall is high enough this will not be a problem but if there is mould growth on the wooden studs a complete demolition of the infill walls and replacement with new well insulated infill walls should be considered.

The idea to improve the air tightness by demolishing the original façade and putting a new vapor barrier on the outside of the infill walls was not calculated. WUFI 2D is not a suitable tool since three dimensional moisture transfer have to be taken into account. The moisture exchange between wooden studs and mineral wool must be considered as well as the risk of air leakage. There is little experience about how air tight the studied house type can get when just sealing joints and it could be important to install a new air tight barrier to reach good air tightness. Table 5 in chapter 6.2.2 gives a picture of the importance of increased air tightness. It shows the reduction of energy cost when the air tightness in the reference building is improved together with a balanced ventilations system. The following can be noted:

- $q_{50}=1.0 \rightarrow q_{50}=0.3$ gives savings of 5791 SEK/yr
- $q_{50}=0.6 \rightarrow q_{50}=0.3$ gives savings of 2235 SEK/yr

If it proves to be difficult to achieve sufficient air tightness by just sealing joints it could be cost effective (based on these numbers of savings per year) to install a new air tight barrier when the façade is demolished. If that is the case it would be interesting to investigate the solution more in order to ensure moisture safety.

It would be interesting to investigate alternative solutions such as different combinations of render on insulation boards. These could have economic benefits, but are generally less moisture safe.

9.4 Indoor comfort

The cold air entering through window airing with the purpose of cooling during early spring will cause comfort problems as well as over-temperatures if there is no airing. Measures must be taken to decrease the over-temperatures, at least for the well-insulated alternatives.

The insolation and heat from household equipment are two sources comparable in size that affects the indoor temperature much. Insolation can be reduced by using some kind of sun-shading. More efficient household equipment would reduce its heat load. Another problem is the temperature of the inlet air that is set to 17°C in the calculations. If it could be lowered without causing comfort problems, for example by using more efficient inlet devices, the overheating problem would also decrease. Other possibilities are temperature drops during night.

The calculated temperatures at the edges of the ground floors suggest that no comfort problem should be expected due to cold floor temperatures. Further studies should be done to check problems by balconies. More accurate results demands transient heat transfer calculations with for example Heat 2.

The problem with draught caused by cold window panes was not investigated.

10 Discussion

Renovation options that are not considered in this work might be more cost efficient to perform than the evaluated ones and should be investigated. Since the space heating energy consumption for the well-insulated alternatives is down at levels of about 50% of the other energy posts it is tempting to look at options to reduce the bought hot water, household and operation energy instead of performing cost inefficient measures to reduce transmission losses. One option is to produce energy in the building by installing solar panels for hot water and electricity. Another is to find even better household equipment. Other options that are not included in the work are different additional insulation solutions such as render on insulation instead of a ventilated facade.

Cost is evaluated with a rather basic LCC-analysis. The only running expenses considered is the cost of energy. Maintenance cost such as painting or washing might be important when comparing different renovation solutions, for example insulation with render. Other costs or benefits that are not considered but could be important are environmental cost, benefits due to increased rentable space and higher market value of the building because of the renovation.

Based on the high investment costs and the payback time of 30-50 years it is likely that most building owners will not be interested in performing very energy-efficient renovations for economic reasons. The society needs to take necessary actions in order to reach the energy goals of 50% decreased energy consumption.

Assessment of thermal indoor climate is based on operative temperature, radiant temperature asymmetry and floor temperatures. No dissatisfying thermal indoor climate was detected with these factors, but earlier investigations have indicated that cold temperatures and draught is a problem for houses from the studied time period. Problems with draught should be more closely investigated.

Durability depends on more than the heat and moisture condition in the wall. Material abrasion for other reasons and factors such as architectural durability and social durability are important to consider.

The methodology has worked well, but there are problems with uncertain input data. Economic calculations over time are always uncertain, but the investment cost could have been evaluated based on the real reference building instead of a similar house and by consulting experts. Another factor is the achievable air tightness for different measures that has strong influence on the energy consumption. Measured data from real completed projects would make this factor more certain. It must also be remembered that the calculation method with well-defined leakages does not represent the reality exactly and that the air infiltration changes with different leakage distribution.

The aim to choose and evaluate some relevant renovation options for the studied house type and find the best solutions was achieved. However, many interesting solutions were not evaluated. The reason is lack of time and difficulties to obtain input data for costs.

Many investigations have been done in this field but works including more than a few factors are rare. There are several Swedish evaluations of energy consumption and cost for renovations, but they rarely include assessments of qualities such as durability and comfort. This work is an attempt to perform a more comprehensive evaluation of renovation alternatives. The results from this work might be used as a part in a greater evaluation, or as a basis for developing a methodology for evaluating renovation alternatives.

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Appendix 1: Steady state model

The steady state energy model that is used in this work is based on steady state conditions and an annual mean temperature difference. U-value of the ground in accordance with the EN 13370:1998

$$Q_{energy} = Q_t + Q_v + Q_l + Q_{hw} + Q_{op,el} - Q_{hr} - Q_g \qquad \text{[kWh/yr]}$$

Where:

Q_t is transmission losses including thermal bridges and boundary effects

$$Q_t = \Delta T t \sum_i (UA)_i + (\Psi L)_i \qquad \text{[kWh]}$$

Q_v is ventilation losses

$$Q_v = \Delta T t \left(\dot{V}\rho c_p\right)_{vent} \qquad \text{[kWh]}$$

Q_l is air leakage losses

$$Q_l = \Delta T t \left(\dot{V}\rho c_p\right)_{leak} = \Delta T t \left((C \cdot P^n)\rho c_p\right)_{leak} \qquad \text{[kWh]}$$

Q_{hw} is the heating of hot water

$$Q_{hw} = \begin{cases} 40A_{temp} & \text{Before renovation} \\ 25A_{temp} & \text{After individual billing and installing smart nozzels} \end{cases} \qquad \text{[kWh/yr]}$$

$Q_{op,el}$ is operation energy (electric energy need for pumps fans etc.)

$$Q_{op,el} = 2tA_{temp} = 17{,}25A_{temp} \qquad \text{[kWh/yr]}$$

Q_{hr} is heat recovery (heat recovered in heat exchangers heat pumps etc.)

$$Q_{hr} = Q_v\eta_v + Q_{hw}\eta_{hw} \qquad \text{[kWh]}$$

Q_g is internal gains from people, lighting, household machines, hot water etc.

$$Q_g = Q_{g,people} + 0{,}8Q_{household} + 0{,}2Q_{hw} + Q_{sun} = \qquad \text{[kWh]}$$

$$= 10{,}5A_{temp} + 39{,}4A_{temp} + 0{,}2\begin{pmatrix} 40A_{temp} \\ 25A_{temp} \end{pmatrix} + 0 \qquad \text{[kWh/yr]}$$

Energy for producing hot water is set to Warfvinges suggestion in VVS Företagen (2009): 40 kWh/m^2/yr before renovation and 40-15=25 kWh/m^2/yr after renovation.

Heat recovery energy is calculated from the efficiency of the heat exchangers.

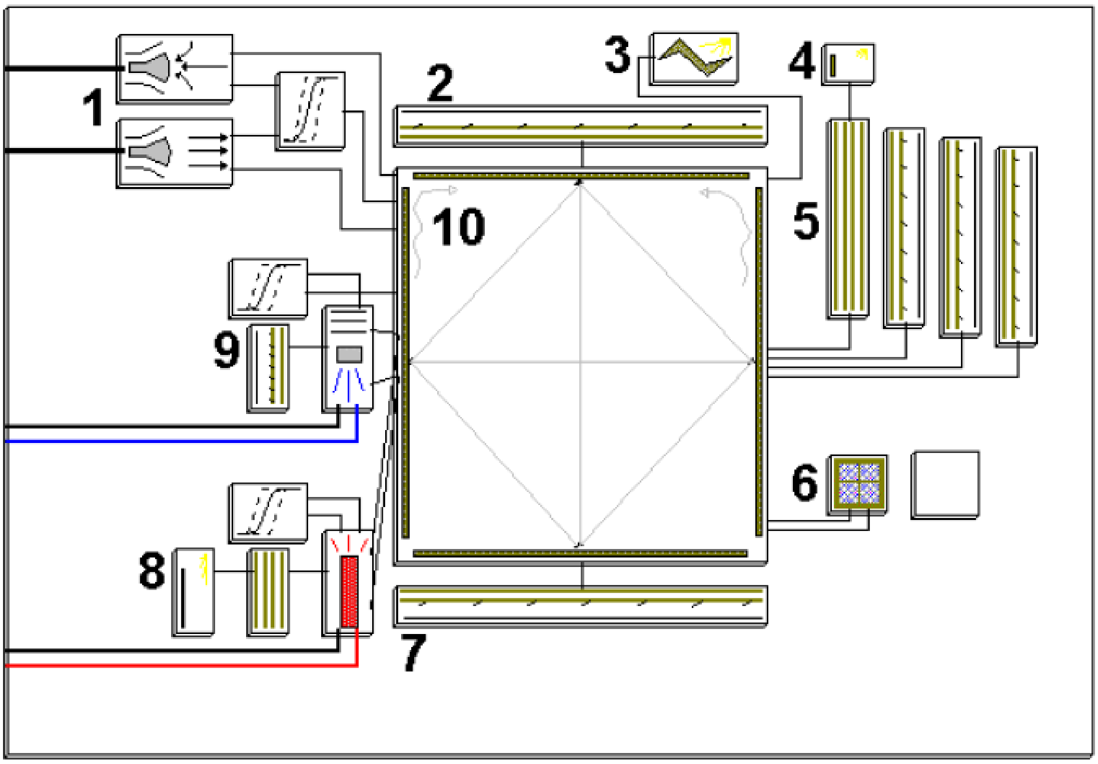
The internal heat gains include electrical equipment, people and hot water. Solar radiation is neglected (set to zero).

Based on the guidelines in Pettersson (2007) the heat gain from electrical equipment is approximated to 80% of the household electricity consumption (which is set to 4,5 W/m^2 = 39.4 kWh/m^2/yr and the gains from hot water to 20% of the hot water heating energy.

The gain from people is set to 60 W/person with 2 persons per 50m^2 which gives 1.2 W/m^2 = 10.5 kWh/m^2/yr.

Appendix 2: IDA model

Each energy post described in the energy consumption chapter is coupled according to the figure below showing one zone in IDA. The model of the building consists of three zones, one for each storey that in turn are coupled.



1. Supply and exhaust air terminals (VAV), with controller
2. Ceiling
3. Air leak to ambient
4. Solar irradiation and external film coefficient, external wall
5. External wall and interior walls
6. Window and shading calculation component
7. Floor
8. Radiator with controller and wall portion behind radiator (with solar irradiation)
9. Cooling panel with controller and ceiling portion behind
10. The actual zone model in which radiation, convection and loads etc. are modeled

Appendix 3: Results of Heat 2 calculations

Thermal bridges are calculated according to EN ISO 10211:2007. Following results are obtained. The values are interpolated and used as input to the energy calculation.

		Thermal bridges [W/(m·K)]							
	$t_{tot}=t_1+t_2+t_3$ [mm]	Windows 1	Windows 2	Windows 3	Beam foundation	Roof-Wall	Internal Slab or wall	Balcony	Vertical wall-wall
Original	0	-	-	0.0278	0.1688	0.153	0.1256	0.1256	0.1968
Pilot	340	-	0.042	-	-0.0125	0.0233	0.0036	0.0099	0.0479
No demolition	50	0.0693	0.042	0.0278	-0.0204	0.0819	0.0485	0.0988	0.1291
	100	0.0759	0.042	0.0423	-0.0464	0.06085	0.0278	0.1046	0.1035
	150	0.0846	0.042	0.0489	-0.0569	0.0398	0.0179	0.1108	0.0875
	200	0.0911	0.042	0.0576	-0.0609	0.0329	0.0125	0.1148	0.0766
	250	0.0911	0.042	0.0641	-0.0626	0.026	0.0094	0.1176	0.0697
Partial demolition	50	0.0693	-	-	0.1677	0.0585			
	100	0.0759	0.042	-	0.159	0.0504	0.0515	0.0948	0.1234
	150	0.0846	0.042	-	0.1533	0.0423	0.0304	0.1001	0.0974
	200	0.0911	0.042	-	-0.0156	0.0392	0.0202	0.1049	0.0825
	250	0.0911	0.042	-	-0.0382	0.0361	0.0145	0.1083	0.0728
	350	0.0911	0.042	-	-0.0519	0.0233	0.0072	0.1121	0.0551

Windows 1: Original windows original location

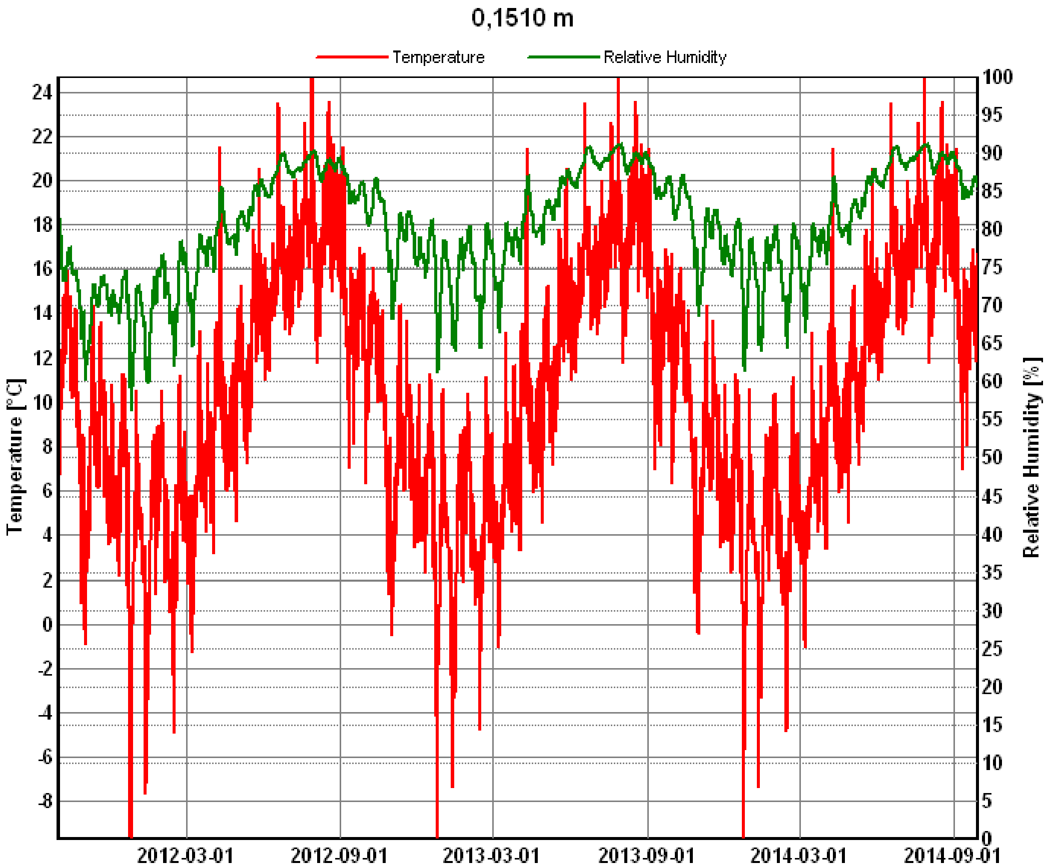
Windows 2 : New windows new location

Windows 3: New windows original location

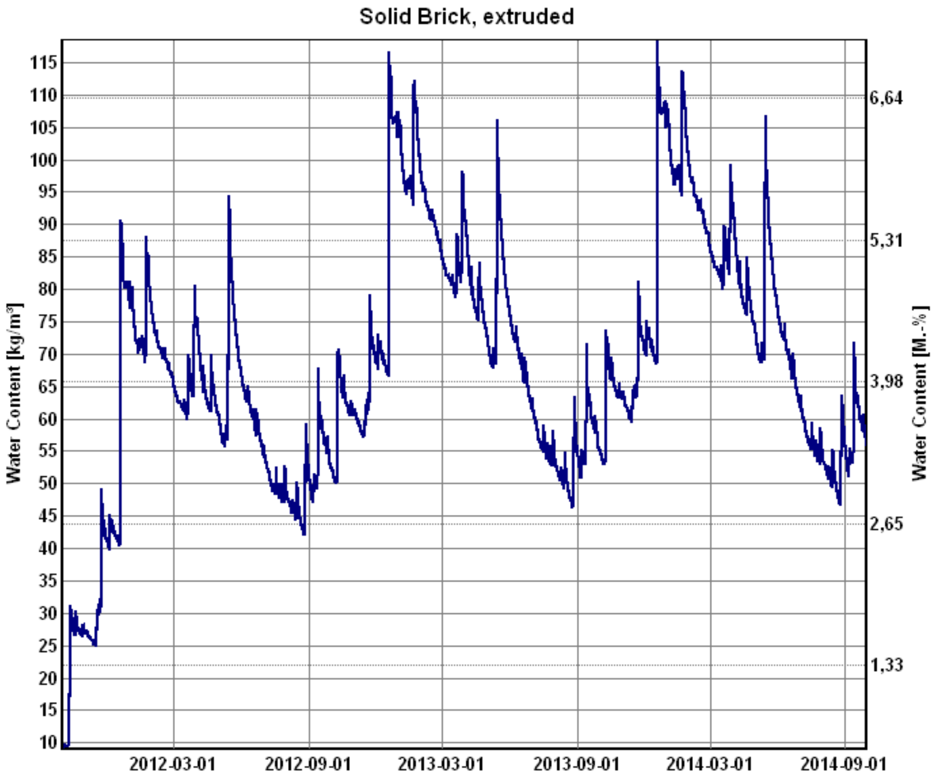
Appendix 4: Results of the WUFI calculations

The commented calculations in WUFI gives the following results.

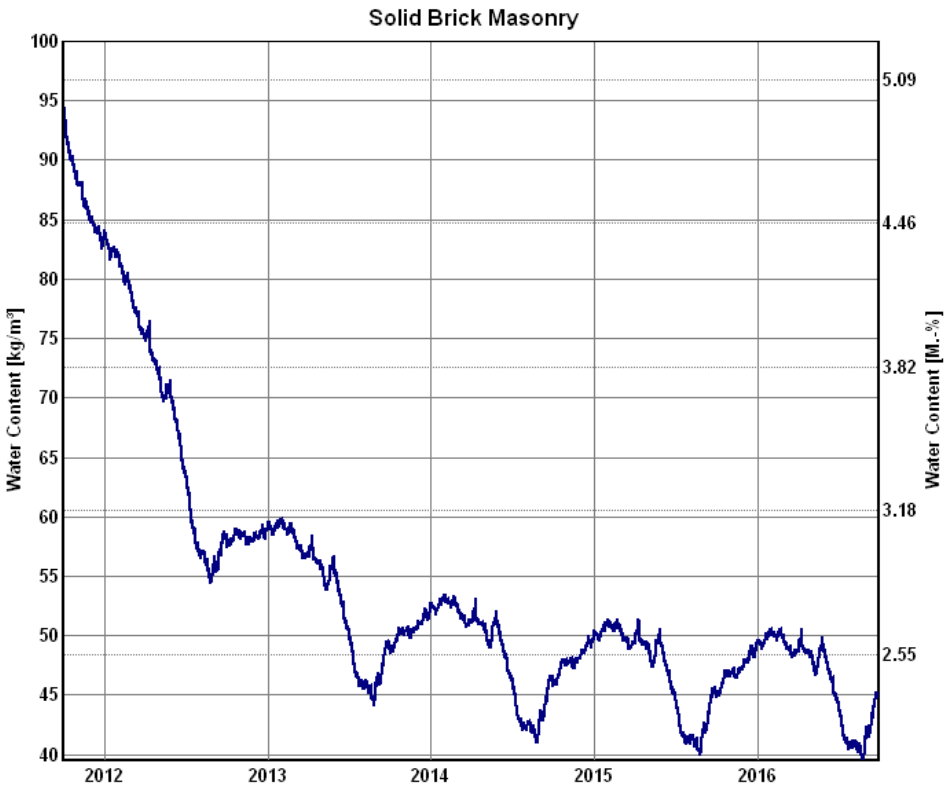
Temperature and relative humidity by the exterior edge of the studs in the original building:



Moisture content in the original brick leaf of the cavity wall:



Moisture content when adding a ventilated panel on the original leaf



Appendix 5: Investment costs in the LCC-analysis

Investment cost for measures according to (Jansson Berggren Sundqvist 2008) Values are interpolated when exact numbers are missing.						
Installation of balanced ventilation system with heat exchanger						
		SEK/A_{temp}	Atemp	cost		
Central η=0.6		337	1016	342351		
Central η=0.8		388	1016	394158		
Additional insulation on original brick facade. New facade						
	t_{tot}	SEK/m^2	A_{wall}	cost		
	70	1250	529	661250		*L1*
	200	1475	529	780275		*I1*
	300	1625	529	859625		*H1*
Aditional insulation (mineral wool) demolition of existing brick facade, new facade						
	70	1285	529	679765		*L2*
	200	1675	529	886075		*I2*
	300	1975	529	1044775		*I2/H2*
	400	2275	529	1203475		*H2*
	420	2335	162	378270		*Pilot renovation*
Additional insulation on attic (existing insulation stays)						
	250	150	362	54300		
Change windows and doors to very efficient windows						
		SEK/#	#	cost		
		6555	96	629280		
Beam foundation thermal bridge insulation						
	t	SEK/m	l_{beam}	cost		t_{tot}
	30	308	90,4	27843		*300*
	50	318	90,4	28747		*400*
	110	346	90,4	31278		*440*
	150	365	90,4	32996		
	200	389	90,4	35166		
Air tightness						
		SEK/#	#	cost		
Tightening around windows and doors		2257	96	216672		
Leakage search + tightening		2604	96	249984		

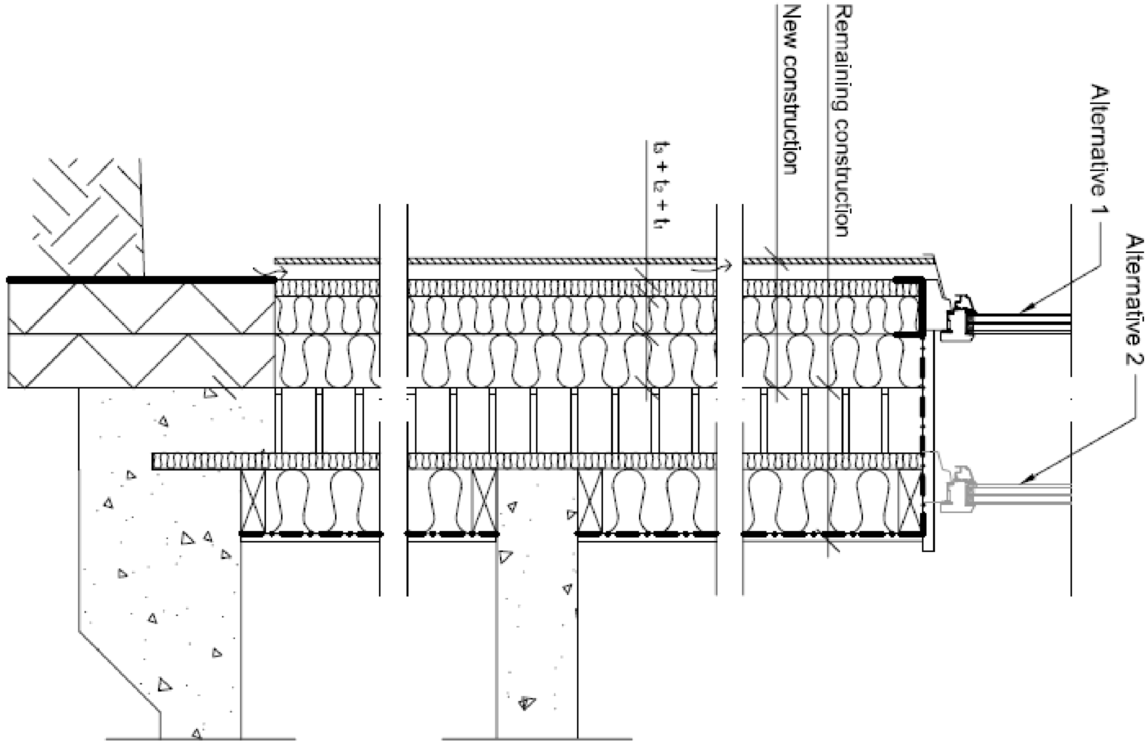
Decreased water consumption					
Individual billing	31,25	1016	31719		
Flow limiting taps	76,25	1016	77394		
Energy efficient household equipment					
	SEK/m^2	A_{temp}	cost		
	200	1016	203000		
Assumed values (not available in (Jansson Berggren Sundqvist 2008))					
	SEK/m2	Area	cost		
Demolition of infill walls add new ins thickness 440mm					
	3200	368	1177600		*Pilot*
Blown mineral fiber filling of existing air gap					
	200	178	35600		
Internal additional insulation of ground slab					
	600	362	217200		
Cut of original balconies and replace with new					
	SEK/#	#	cost		
	20500	18	369000		
New hot water distribution system					
	SEK/m^2	A_{temp}	cost		
	100	1016	150000		
Repair existing facade and make it moisture safe.					
	SEK/m^2	A_{wall}	cost		
	500	529	264500		
Installation of heat pump					
			20000		

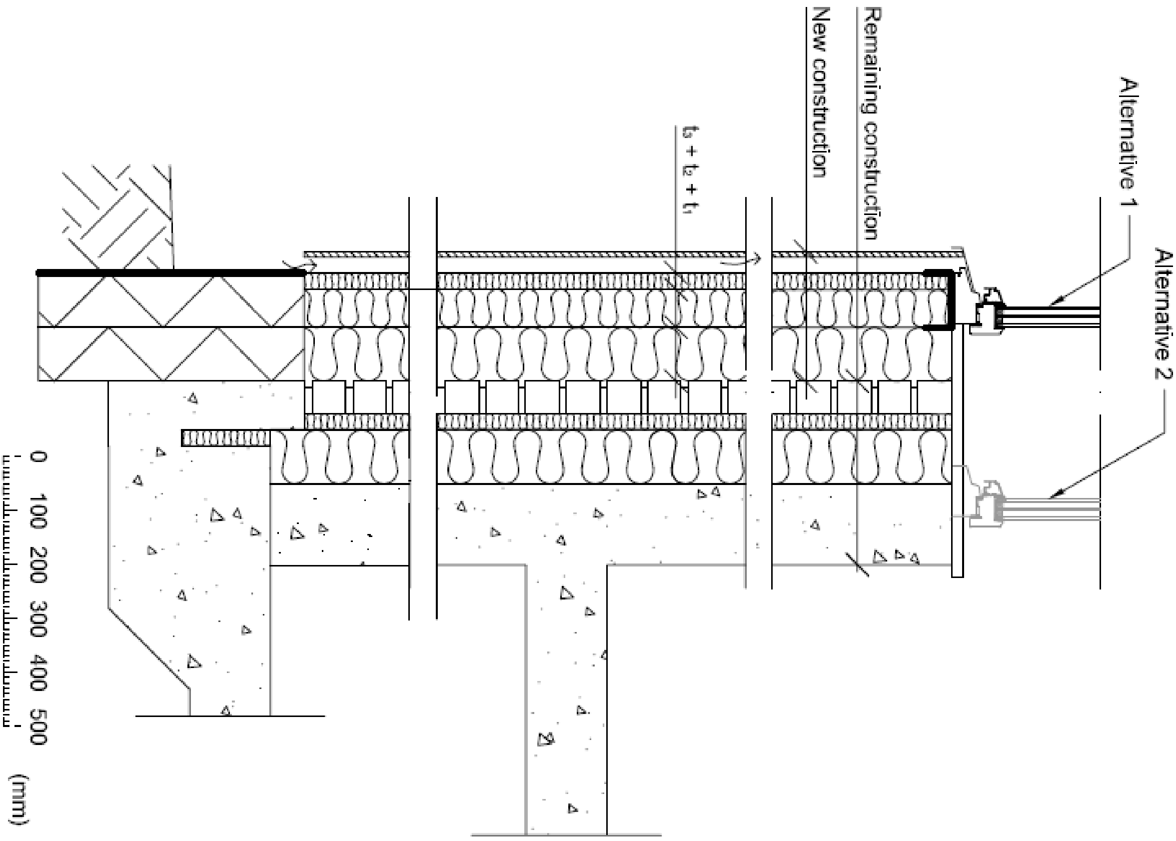
Summed up investment costs for each studied combination:

Combination	SEK
1a Original	0
1b Original + Repair facade	264500
1c Pilot	3482686
2a	20000
2b	592335
2c	644142
2d	644142
2e	644142
2f	644142
3a	499968
3b	1196818
3c	1315843
3d	1395193
3e	1464268
3f	1627468
4a	1608116
4b	2269366
4c	2388391
4d	2503341
4e	2572416
4f	2735616
5a	1825316
5b	2486566
5c	2605591
5d	2720541
5e	2789616
5f	2952816

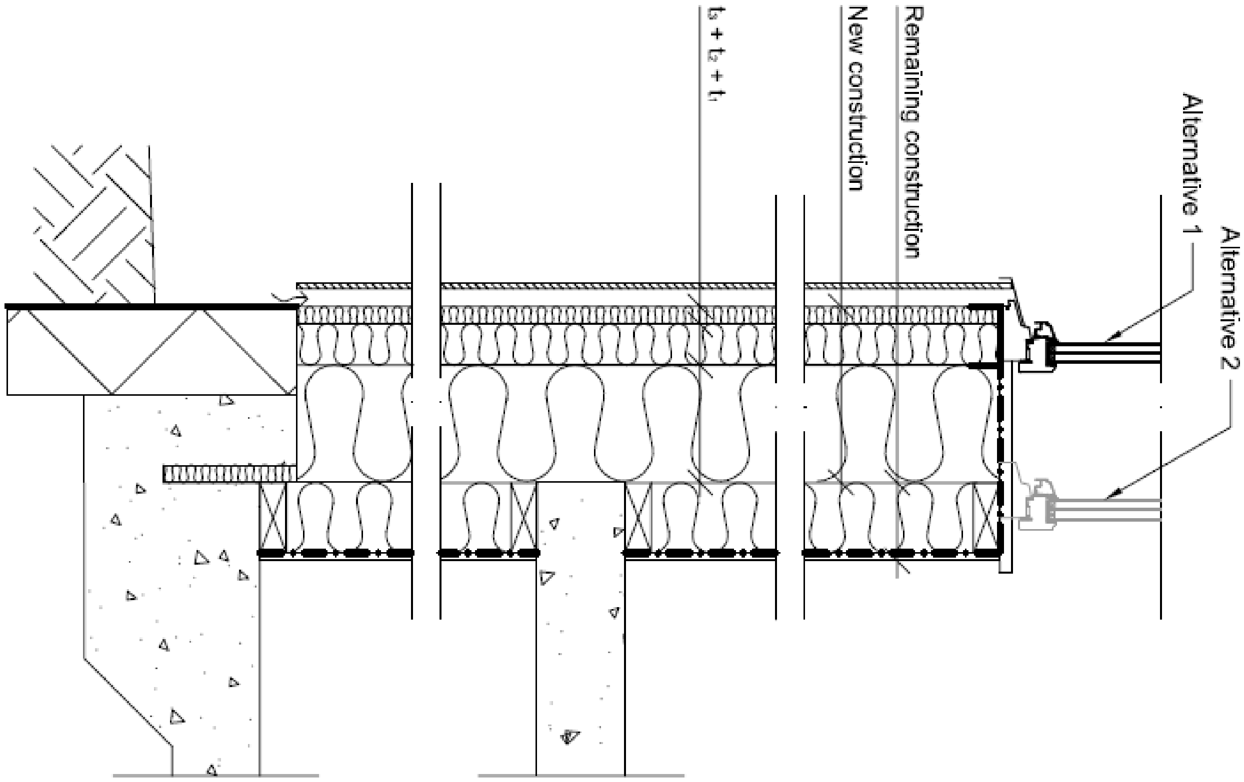
Appendix 6: Drawings

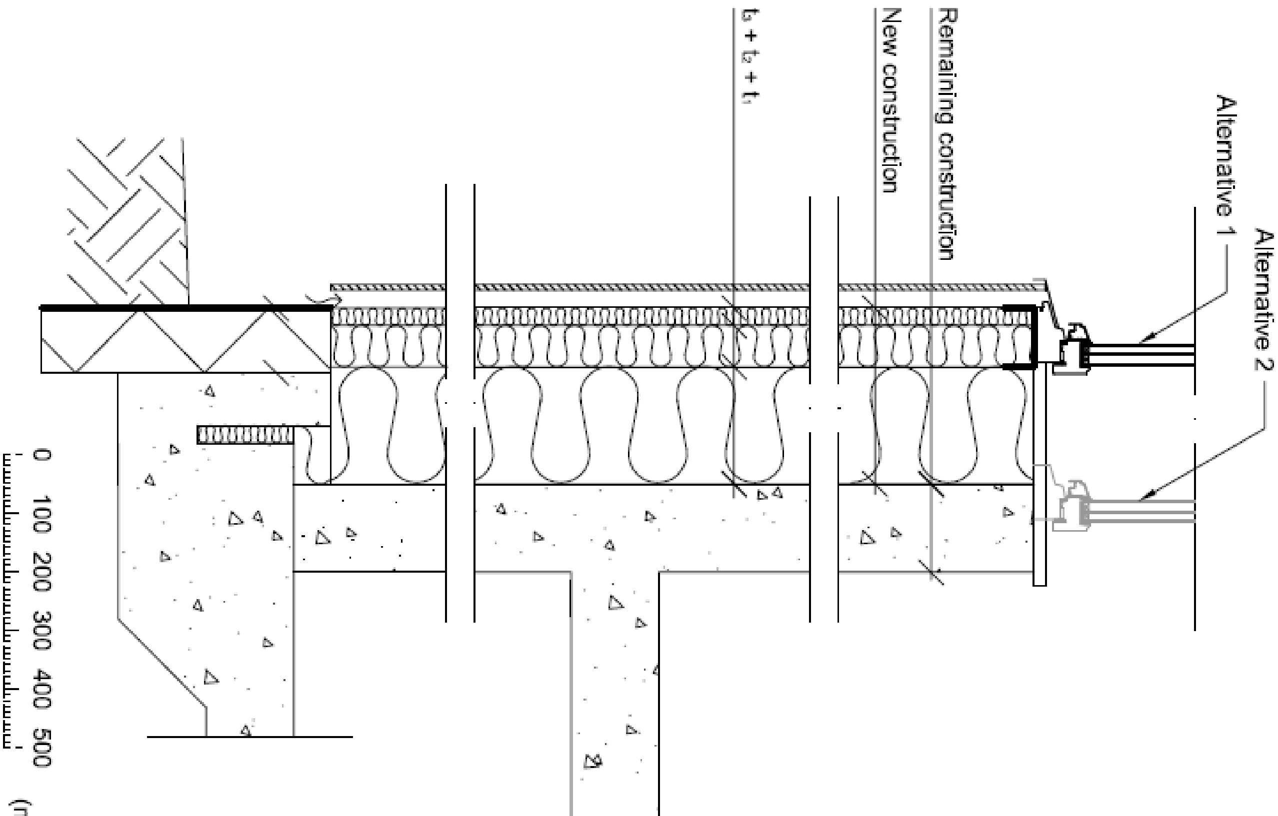
No demolition (Alternative L1, I1 and H1)



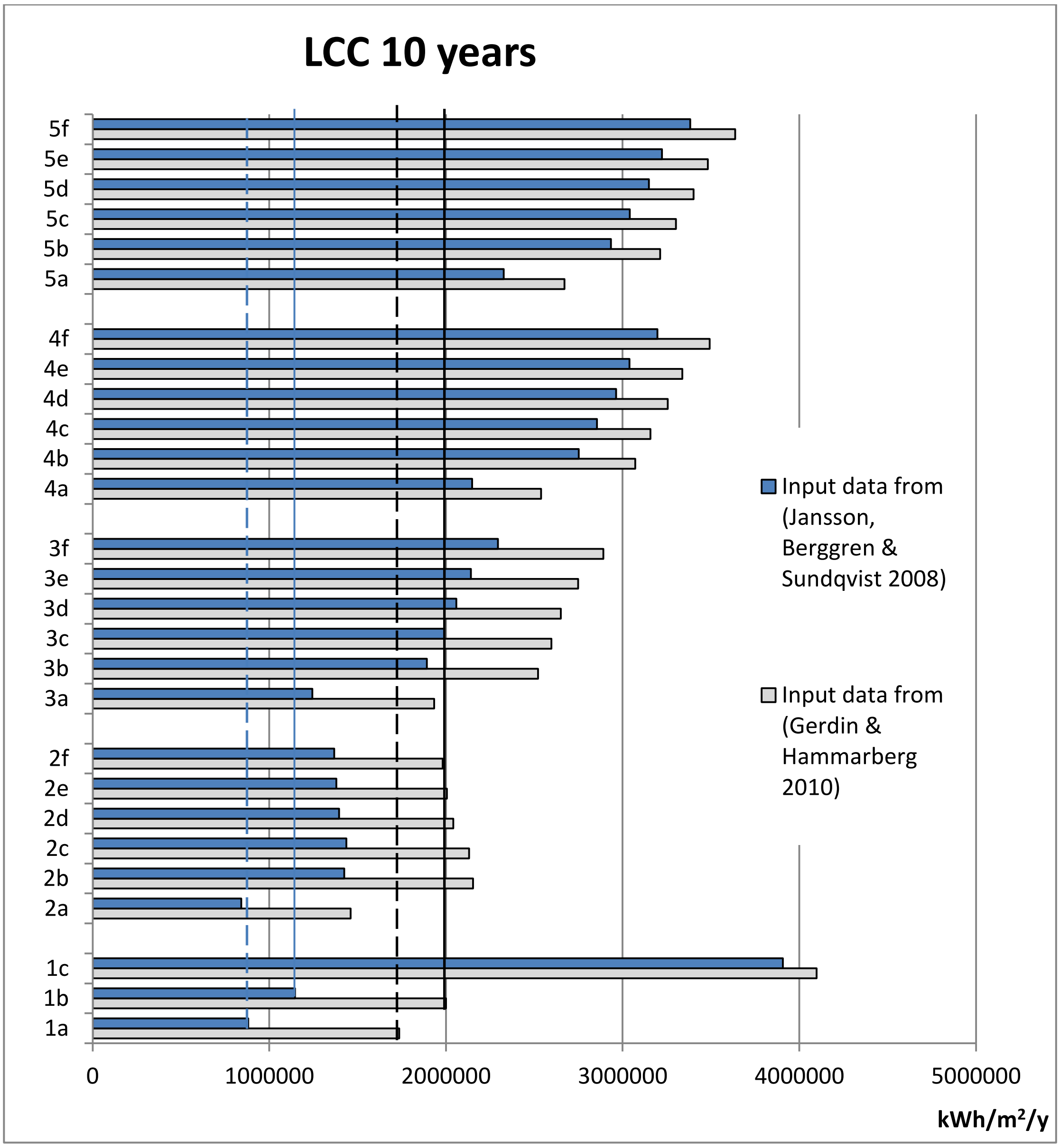


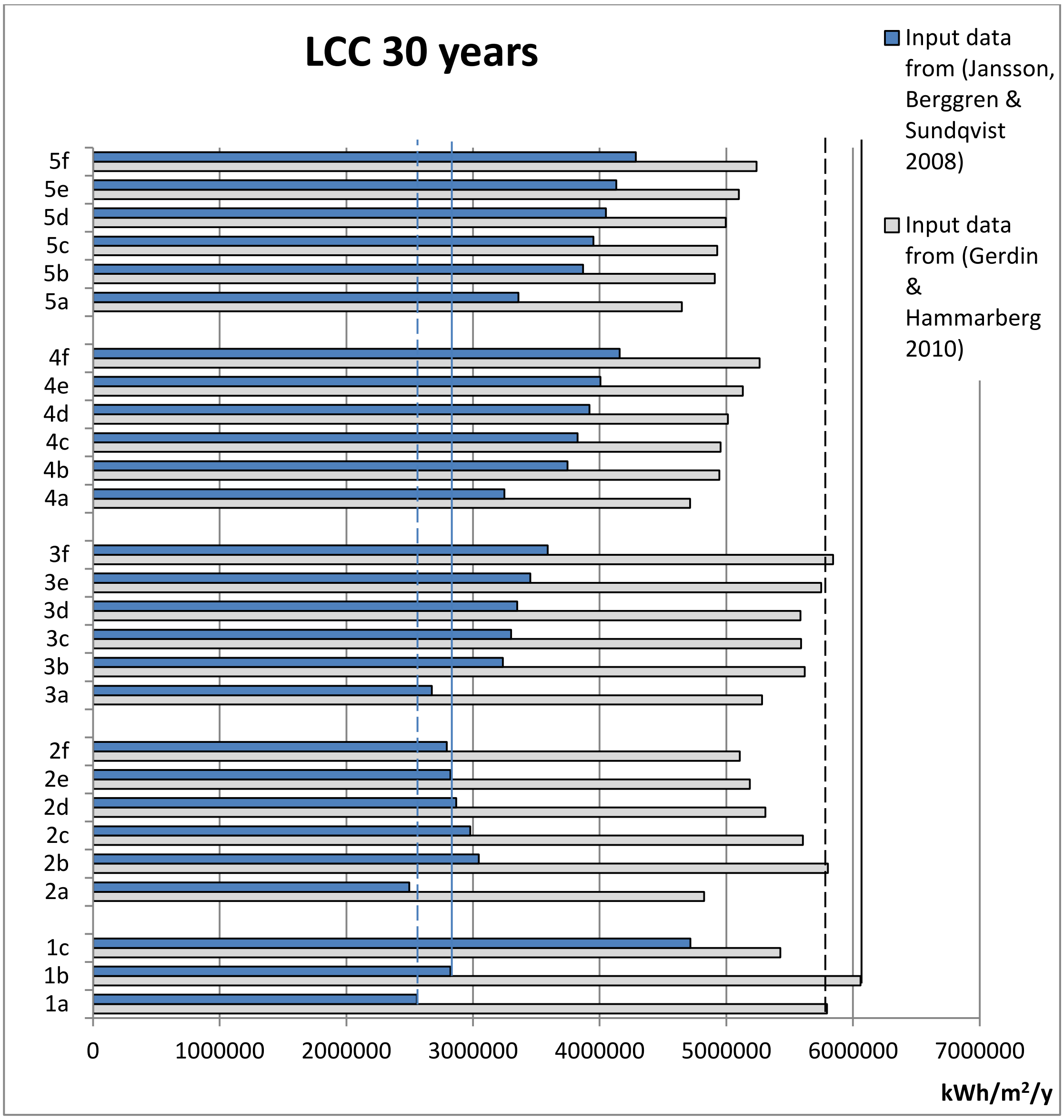
Partial demolition (alternative I2, H2)



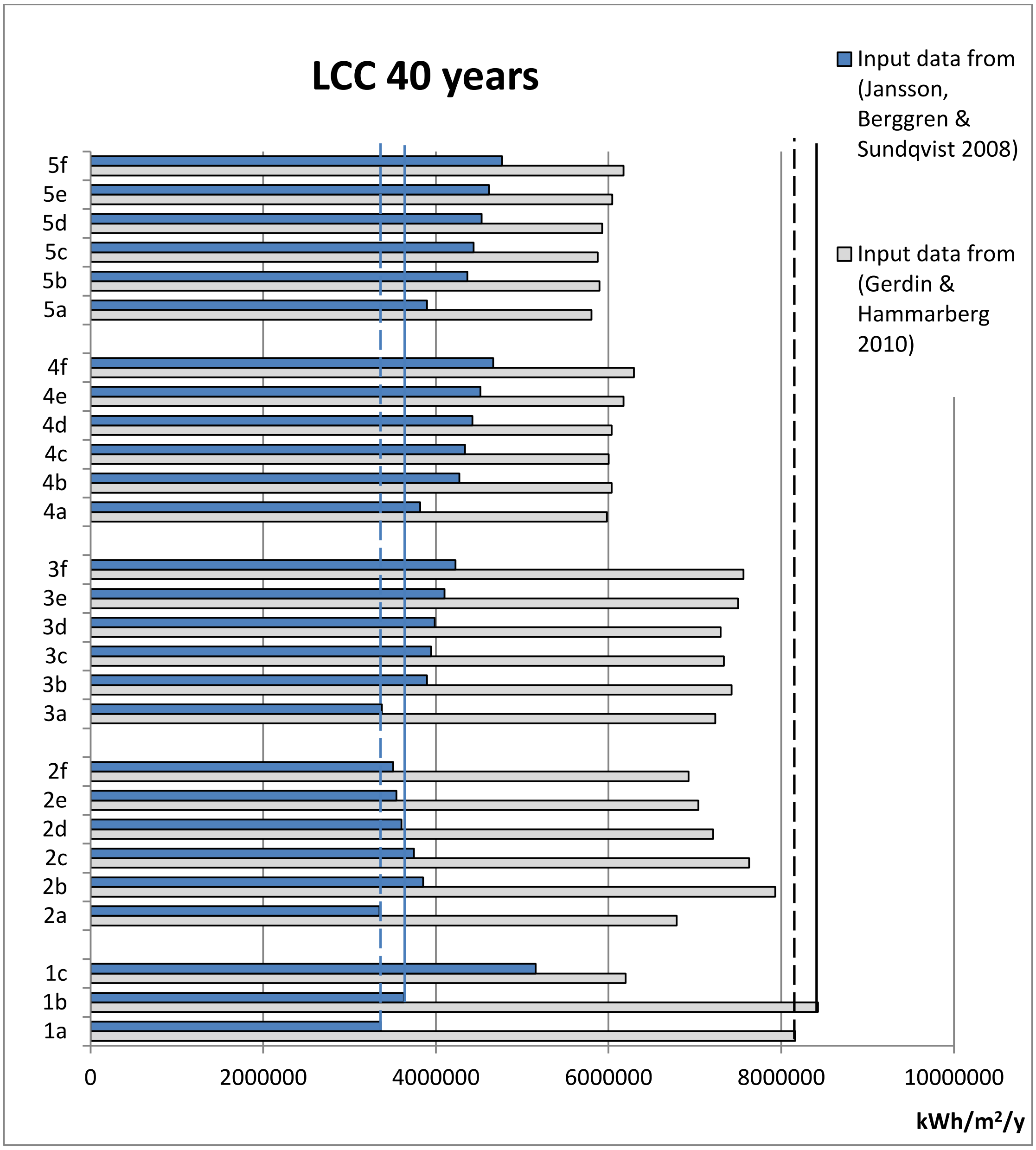


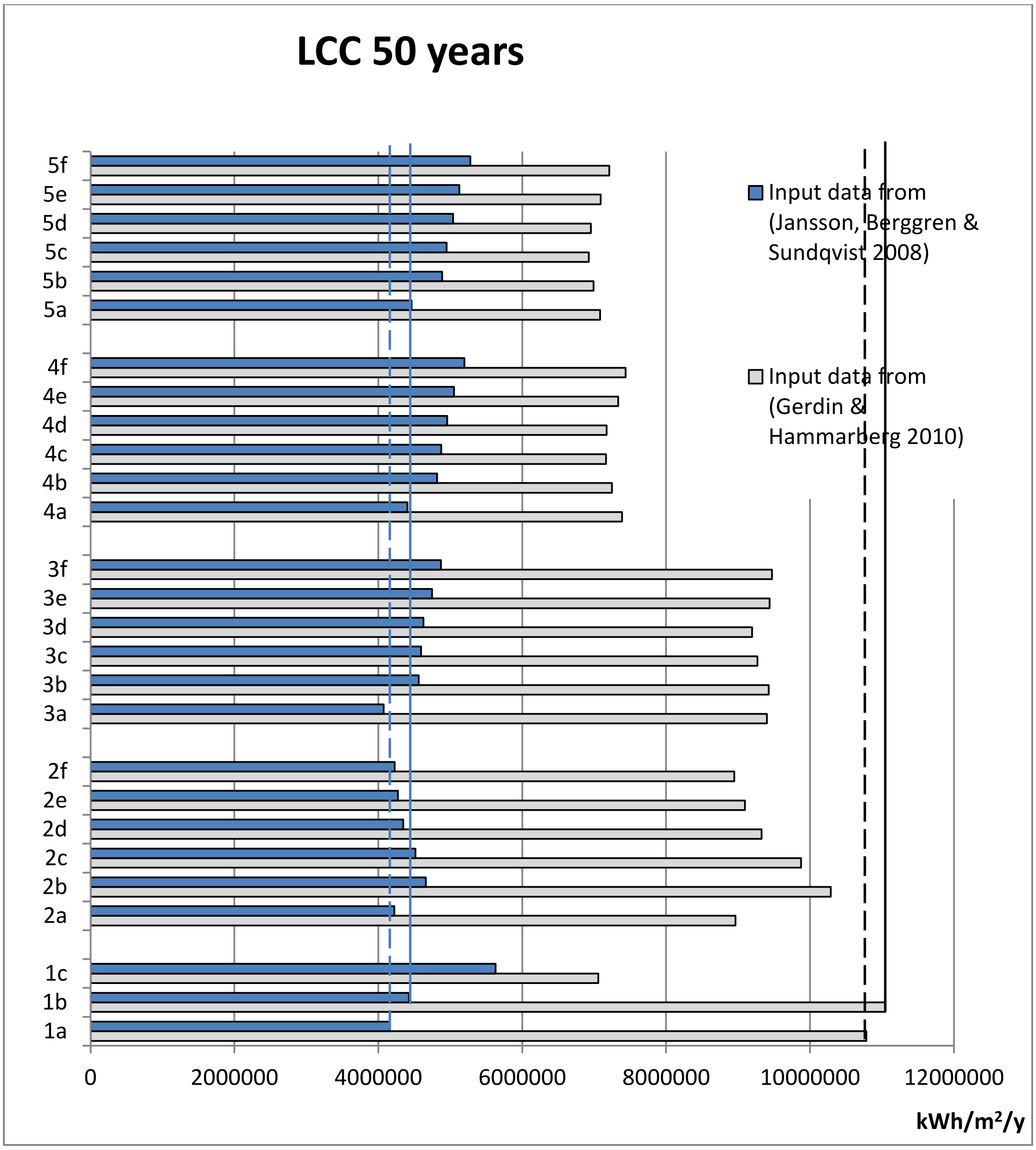
Appendix 7: LCC results





LCC 30 years
Input data from (Jansson, Berggren & Sundqvist 2008)
Input data from (Gerdin & Hammarberg 2010)
5f
5e
5d
5c
5b
5a
4f
4e
4d
4c
4b
4a
3f
3e
3d
3c
3b
3a
2f
2e
2d
2c
2b
2a
1c
1b
1a
0
1000000
2000000
3000000
4000000
5000000
6000000
7000000
kWh/m²/y


LCC 40 years
Input data from (Jansson, Berggren & Sundqvist 2008)
Input data from (Gerdin & Hammarberg 2010)
5f
5e
5d
5c
5b
5a
4f
4e
4d
4c
4b
4a
3f
3e
3d
3c
3b
3a
2f
2e
2d
2c
2b
2a
1c
1b
1a
0
2000000
4000000
6000000
8000000
10000000
kWh/m²/y



LCC 50 years
5f
5e
5d
5c
5b
5a
4f
4e
4d
4c
4b
4a
3f
3e
3d
3c
3b
3a
2f
2e
2d
2c
2b
2a
1c
1b
1a
0
2000000
4000000
6000000
8000000
10000000
12000000
kWh/m²/y
Input data from (Jansson, Berggren & Sundqvist 2008)
Input data from (Gerdin & Hammarberg 2010)

Appendix 8: Studied renovation combinations

1a Original

Building envelope

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	wooden studs+mineral wool
30	air gap	30	mineral wool
60	bricks	120	bricks

Ground		*Roof*	
	plastic mat	150	concrete
50	concrete	180	cellulose insulation
60	sand		
30	mineral wool		
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=3 [W/(m^2·K)]	q_{50}=2 [l/m$^{2\cdot}$s]	K_{bridge}=79 [W/K]
U_{frame}=1,7 [W/(m^2·K)]		
Ψ_{spacer}=0 [W/(m·K)]	*Leakages/Ventholes*	
SHGC=0,7600 [-]	n=0.65	
T=0.6764 [-]	C=	

Ventilation

Flow			0,35l/m2
HEX			η=0
supply air set point temperature			-
temperature rise in vent system			-
	ΔP	*η*	
Supply fan	-	-	
Exhaust fan	400	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	4,45 W/m2
Hot water flow (constant)	0,02317 l/s

1b Pilot

1b Repare original

Building envelope

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	wooden studs+mineral wool
30	air gap	30	mineral wool
60	bricks	120	bricks

Ground		*Roof*	
	plastic mat	150	concrete
50	concrete	180	cellulose insulation
60	sand		
30	mineral wool		
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=3 [W/(m^2·K)]	q_{50}=2 [l/m^2·s]	K_{bridge}=79 [W/K]
U_{frame}=1,7 [W/(m^2·K)]		
Ψ_{spacer}=0 [W/(m·K)]	*Leakages/Ventholes*	
SHGC=0,7600 [-]	n=0.65	
T=0.6764 [-]	C=	

Ventilation

Flow			0,35l/m2
HEX			η=0
supply air set point temperature			-
temperature rise in vent system			-
	ΔP	*η*	
Supply fan	-	-	
Exhaust fan	400	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	4,45 W/m2
Hot water flow (constant)	0,02317 l/s

1c Pilot

Building envelope

Load bearing wall		*Infill wall*	
150	concrete	13	gypsum board
220	mineral wool	70	mineral wool+studs
170	mineral wool + studs	170	mineral wool
30	mineral wool + studs	170	mineral wool + studs
30	air gap	30	mineral wool
22	brick screen	30	air gap
		22	brick screen

Ground		*Roof*	
	floor sheeting	150	concrete
80	insulation panels λ=0,023	420	blown mineral wool
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=0,5 [W/(m^2·K)]	q_{50}=2 [l/m^2·s]	K_{bridge}=79 [W/K]
U_{frame}=1,1 [W/(m^2·K)]		
Ψ_{spacer}=0,027 [W/(m·K)]		
SHGC=0,7600 [-]		
T=0.6764 [-]		

Ventilation

Flow			0,35l/m2
HEX			η=0
supply air set point temperature			17
temperature rise in vent system			1
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	3,20 W/m2
Hot water flow (constant)	0.0106 l/s

2a: Q50=2, HP COP=3

Building envelope

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	wooden studs+mineral wool
30	air gap	30	mineral wool
60	bricks	120	bricks

Ground		*Roof*	
	plastic mat	150	concrete
50	concrete	180	cellulose insulation
60	sand		
30	mineral wool		
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=3 [W/(m^2·K)]	q_{50}=2 [l/m^2·s]	K_{bridge}=79 [W/K]
U_{frame}=1,7 [W/(m^2·K)]		
Ψ_{spacer}=0 [W/(m·K)]		
SHGC=0,7600 [-]		
T=0.6764 [-]		

Ventilation

Flow			0,35l/m^2
Heat pump			COP=3
supply air set point temperature			17°C
temperature rise in vent system			1°C
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	4,45 W/m2
Hot water flow (constant)	0,02317 l/s

2b: Q50=2, HEX η=0.6

Building envelope

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	wooden studs+mineral wool
30	air gap	30	mineral wool
60	bricks	120	bricks

Ground		*Roof*	
	plastic mat	150	concrete
50	concrete	180	cellulose insulation
60	sand		
30	mineral wool		
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=3 [W/(m^2·K)]	q_{50}=2 [l/m^2·s]	K_{bridge}=79 [W/K]
U_{frame}=1,7 [W/(m^2·K)]		
Ψ_{spacer}=0 [W/(m·K)]		
SHGC=0,7600 [-]		
T=0.6764 [-]		

Ventilation

Flow			0,35l/m2
HEX			η=0,6
supply air set point temperature			17°C
temperature rise in vent system			1°C
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	4,45 W/m2
Hot water flow (constant)	0,02317 l/s

2c: Q50=2, η=0.8

Building envelope

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	wooden studs+mineral wool
30	air gap	30	mineral wool
60	bricks	120	bricks

Ground		*Roof*	
	plastic mat	150	concrete
50	concrete	180	cellulose insulation
60	sand		
30	mineral wool		
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=3 [W/(m^2·K)]	q_{50}=2 [l/m^2·s]	K_{bridge}=79 [W/K]
U_{frame}=1,7 [W/(m^2·K)]		
Ψ_{spacer}=0 [W/(m·K)]		
SHGC=0,7600 [-]		
T=0.6764 [-]		

Ventilation

Flow			0,35l/m^2
HEX			η=0,8
supply air set point temperature			17°C
temperature rise in vent system			1°C
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	4,45 W/m2
Hot water flow (constant)	0,02317 l/s

2d: Q50=1, η=0.8

Building envelope

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	wooden studs+mineral wool
30	air gap	30	mineral wool
60	bricks	120	bricks

Ground		*Roof*	
	plastic mat	150	concrete
50	concrete	180	cellulose insulation
60	sand		
30	mineral wool		
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=3 [W/(m^2·K)]	q_{50}=1 [l/m$^{2\cdot}$s]	K_{bridge}=79 [W/K]
U_{frame}=1,7 [W/(m^2·K)]		
Ψ_{spacer}=0 [W/(m·K)]		
SHGC=0,7600 [-]		
T=0.6764 [-]		

Ventilation

Flow			0,35l/m^2
HEX			η=0,8
supply air set point temperature			17°C
temperature rise in vent system			1°C
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	4,45 W/m2
Hot water flow (constant)	0,02317 l/s

2e: Q50=0.6, η=0.8

Building envelope

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	wooden studs+mineral wool
30	air gap	30	mineral wool
60	bricks	120	bricks

Ground		*Roof*	
	plastic mat	150	concrete
50	concrete	180	cellulose insulation
60	sand		
30	mineral wool		
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=3 [W/(m^2·K)]	q_{50}=0,6 [l/m$^{2\cdot}$s]	K_{bridge}=79 [W/K]
U_{frame}=1,7 [W/(m^2·K)]		
Ψ_{spacer}=0 [W/(m·K)]		
SHGC=0,7600 [-]		
T=0.6764 [-]		

Ventilation

Flow			0,35l/m^2
HEX			η=0,8
supply air set point temperature			17°C
temperature rise in vent system			1°C
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	4,45 W/m2
Hot water flow (constant)	0,02317 l/s

2f: Q50=0.3, η=0.8

Building envelope

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	wooden studs+mineral wool
30	air gap	30	mineral wool
60	bricks	120	bricks

Ground		*Roof*	
	plastic mat	150	concrete
50	concrete	180	cellulose insulation
60	sand		
30	mineral wool		
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=3 [W/(m^2·K)]	q_{50}=0,3 [l/m$^{2\cdot}$s]	K_{bridge}=79 [W/K]
U_{frame}=1,7 [W/(m^2·K)]		
Ψ_{spacer}=0 [W/(m·K)]		
SHGC=0,7600 [-]		
T=0.6764 [-]		

Ventilation

Flow			0,35l/m^2
HEX			η=0,8
supply air set point temperature			17°C
temperature rise in vent system			1°C
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	4,45 W/m2
Hot water flow (constant)	0,02317 l/s

3a: Q50=0.6, new windows

Building envelope	10		
Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	wooden studs+mineral wool
30	air gap	30	mineral wool
60	bricks	120	bricks

Ground		*Roof*	
	plastic mat	150	concrete
50	concrete	180	cellulose insulation
60	sand		
30	mineral wool		
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=0,5 [W/(m^2·K)]	q_{50}=0,6 [l/m$^{2\cdot}$s]	K_{bridge}=79 [W/K]
U_{frame}=1,1 [W/(m^2·K)]		
Ψ_{spacer}=0,027 [W/(m·K)]		
SHGC=0,6916 [-]		
T=0,5776 [-]		

Ventilation

Flow			0,35l/m^2
HEX			no
supply air set point temperature			17°C
temperature rise in vent system			1°C
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	4,45 W/m2
Hot water flow (constant)	0,02317 l/s

3b: Q50=0.6, L1 (additional insulation no demolition), new windows

Building envelope 10

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	wooden studs+mineral wool
30	blown mineral wool	30	mineral wool
60	bricks	120	bricks
70	mineral wool + studs	70	mineral wool + studs
30	air gap	30	air gap
22	brick screen	22	brick screen

Ground		*Roof*	
	plastic mat	150	concrete
50	concrete	180	cellulose insulation
60	sand		
30	mineral wool		
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=0,5 [W/(m^2·K)]	q_{50}=0,6 [l/m^2·s]	K_{bridge}=44 [W/K]
U_{frame}=1,1 [W/(m^2·K)]		
Ψ_{spacer}=0,027 [W/(m·K)]		
SHGC=0,6916 [-]		
T=0,5776 [-]		

Ventilation

Flow			0,35l/m^2
HEX			no
supply air set point temperature			17°C
temperature rise in vent system			1°C
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	4,45 W/m2
Hot water flow (constant)	0,02317 l/s

3c: Q50=0.6, I1 (additional insulation no demolition), new windows

Building envelope 10

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	wooden studs+mineral wool
30	blown mineral wool	30	mineral wool
60	bricks	120	bricks
200	mineral wool + studs	200	mineral wool + studs
30	air gap	30	air gap
22	brick screen	22	brick screen

Ground		*Roof*	
	plastic mat	150	concrete
50	concrete	180	cellulose insulation
60	sand		
30	mineral wool		
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=0,5 [W/(m^2·K)]	q_{50}=0,6 [l/m^2·s]	K_{bridge}=34 [W/K]
U_{frame}=1,1 [W/(m^2·K)]		
Ψ_{spacer}=0,027 [W/(m·K)]		
SHGC=0,6916 [-]		
T=0,5776 [-]		

Ventilation

Flow			0,35l/m^2
HEX			no
supply air set point temperature			17°C
temperature rise in vent system			1°C
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	4,45 W/m2
Hot water flow (constant)	0,02317 l/s

3d: Q50=0.6, H1 (additional insulation no demolition), new windows

Building envelope 10

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	wooden studs+mineral wool
30	blown mineral wool	30	mineral wool
60	bricks	120	bricks
100	mineral wool	100	mineral wool
200	mineral wool + studs	200	mineral wool + studs
30	air gap	30	air gap
22	brick screen	22	brick screen

Ground		*Roof*	
	plastic mat	150	concrete
50	concrete	180	cellulose insulation
60	sand		
30	mineral wool		
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=0,5 [W/(m^2·K)]	q_{50}=0,6 [l/m^2·s]	K_{bridge}=31 [W/K]
U_{frame}=1,1 [W/(m^2·K)]		
Ψ_{spacer}=0,027 [W/(m·K)]		
SHGC=0,6916 [-]		
T=0,5776 [-]		

Ventilation

Flow			0,35l/m^2
HEX			no
supply air set point temperature			17°C
temperature rise in vent system			1°C
Cventholes=0.115	Cleak=0.069		n=0.65
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	4,45 W/m2
Hot water flow (constant)	0,02317 l/s

3e: Q50=0.6, I2 (additional insulation partial demolition), new windows

Building envelope

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	mineral wool +studs
200	mineral wool + studs	200	mineral wool + studs
30	air gap	30	air gap
22	brick screen	22	brick screen

Ground		*Roof*	
	plastic mat	150	concrete
50	concrete	180	cellulose insulation
60	sand		
30	mineral wool		
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=0,5 [W/(m^2·K)]	q_{50}=0,6 [l/m^2·s]	K_{bridge}=38 [W/K]
U_{frame}=1,1 [W/(m^2·K)]		
Ψ_{spacer}=0,027 [W/(m·K)]		
SHGC=0,6916 [-]		
T=0,5776 [-]		

Ventilation

Flow			0,35l/m^2
HEX			no
supply air set point temperature			17°C
temperature rise in vent system			1°C
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	4,45 W/m2
Hot water flow (constant)	0,02317 l/s

3f: Q50=0.6, H2 (additional insulation partial demolition), new windows

Building envelope

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
200	mineral wool	120	mineral wool +studs
200	mineral wool + studs	100	mineral wool
30	air gap	200	mineral wool + studs
22	brick screen	30	air gap
		22	brick screen

Ground		*Roof*	
	plastic mat	150	concrete
50	concrete	180	cellulose insulation
60	sand		
30	mineral wool		
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=0,5 [W/(m^2·K)]	q_{50}=0,6 [l/m^2·s]	K_{bridge}=32 [W/K]
U_{frame}=1,1 [W/(m^2·K)]		
Ψ_{spacer}=0,027 [W/(m·K)]		
SHGC=0,6916 [-]		
T=0,5776 [-]		

Ventilation

Flow			0,35l/m^2
HEX			no
supply air set point temperature			17°C
temperature rise in vent system			1°C
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	4,45 W/m2
Hot water flow (constant)	0,02317 l/s

4a: Q50=0.6, original wall, balanced vent, attic insulation, hot water reduction, electricity reduction

Building envelope

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	wooden studs+mineral wool
30	air gap	30	mineral wool
60	bricks	120	bricks

Ground		*Roof*	
	plastic mat	150	concrete
50	concrete	420	blown mineral wool
60	sand		
30	mineral wool		
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=0,5 [W/(m^2·K)]	q_{50}=0,6 [l/m$^{2\cdot}$s]	K_{bridge}=79 [W/K]
U_{frame}=1,1 [W/(m^2·K)]		
Ψ_{spacer}=0,027 [W/(m·K)]		
SHGC=0,6916 [-]		
T=0,5776 [-]		

Ventilation

Flow			0,35l/m^2
HEX			η=0,8
supply air set point temperature			17°C
temperature rise in vent system			1°C
Cventholes=0	Cleak=0.069		n=0.65
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C	
Equipment	3,20 W/m2	
Hot water flow (constant)	0,0159 l/s	flow reductive nozzels

4b: Q50=0.6, L1 (additional insulation no demolition), balanced vent, attic insulation, hot water reduction, electricity reduction

Building envelope

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	wooden studs+mineral wool
30	blown mineral fibres	30	mineral wool
60	bricks	120	bricks
70	mineral wool + studs	70	mineral wool + studs
30	air gap	30	air gap
22	brick screen	22	brick screen

Ground		*Roof*	
	plastic mat	150	concrete
50	concrete	420	blown mineral wool
60	sand		
30	mineral wool		
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=0,5 [W/(m^2·K)]	q_{50}=0,6 [l/m$^{2\cdot}$s]	K_{bridge}=34 [W/K]
U_{frame}=1,1 [W/(m^2·K)]		
Ψ_{spacer}=0,027 [W/(m·K)]		
SHGC=0,6916 [-]		
T=0,5776 [-]		

Ventilation

Flow			0,35l/m^2
HEX			η=0,8
supply air set point temperature			17°C
temperature rise in vent system			1°C
Cventholes=0	Cleak=0.069		n=0.65
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	3,20 W/m2
Hot water flow (constant)	0,0159 l/s

4c: Q50=0.6, I1 (additional insulation no demolition), balanced vent, attic insulation, hot water reduction, electricity reduction

Building envelope 10

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	wooden studs+mineral wool
30	blown mineral fibres	30	mineral wool
60	bricks	120	bricks
170	mineral wool + studs	170	mineral wool + studs
30	air gap	30	air gap
22	brick screen	22	brick screen

Ground		*Roof*	
	plastic mat	150	concrete
50	concrete	420	blown mineral wool
60	sand		
30	mineral wool		
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=0,5 [W/(m^2·K)]	q_{50}=0,6 [l/m^2·s]	K_{bridge}=34 [W/K]
U_{frame}=1,1 [W/(m^2·K)]		
Ψ_{spacer}=0,027 [W/(m·K)]		
SHGC=0,6916 [-]		
T=0,5776 [-]		

Ventilation

Flow			0,35l/m^2
HEX			η=0,8
supply air set point temperature			17°C
temperature rise in vent system			1°C
Cventholes=0	Cleak=0.069		n=0.65
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	3,20 W/m2
Hot water flow (constant)	0,0159 l/s

4d: Q50=0.6, H1 (additional insulation no demolition), balanced vent, attic insulation

Building envelope 10

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	wooden studs+mineral wool
30	blown mineral fibres	30	mineral wool
60	bricks	120	bricks
100	mineral wool	100	mineral wool
170	mineral wool + studs	170	mineral wool + studs
30	air gap	30	air gap
22	brick screen	22	brick screen

Ground		*Roof*	
	plastic mat	150	concrete
50	concrete	420	cellulose insulation
60	sand		
30	mineral wool		
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=0,5 [W/(m^2·K)]	q_{50}=0,6 [l/m$^{2\cdot}$s]	K_{bridge}=31 [W/K]
U_{frame}=1,1 [W/(m^2·K)]		
Ψ_{spacer}=0,027 [W/(m·K)]		
SHGC=0,6916 [-]		
T=0,5776 [-]		

Ventilation

Flow			0,35l/m^2
HEX			η=0,8
supply air set point temperature			17°C
temperature rise in vent system			1°C
Cventholes=0	Cleak=0.069		n=0.65
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	3,20 W/m2
Hot water flow (constant)	0,0159 l/s

4e: Q50=0.6, I2 (additional insulation partial demolition), balanced vent, attic insulation

Building envelope

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	mineral wool +studs
200	mineral wool + studs	200	mineral wool + studs
30	air gap	30	air gap
22	brick screen	22	brick screen

Ground		*Roof*	
	plastic mat	150	concrete
50	concrete	420	cellulose insulation
60	sand		
30	mineral wool		
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=0,5 [W/(m^2·K)]	q_{50}=0,6 [l/m^2·s]	K_{bridge}=31 [W/K]
U_{frame}=1,1 [W/(m^2·K)]		
Ψ_{spacer}=0,027 [W/(m·K)]		
SHGC=0,6916 [-]		
T=0,5776 [-]		

Ventilation

Flow			0,35l/m^2
HEX			η=0,8
supply air set point temperature			17°C
temperature rise in vent system			1°C
Cventholes=0	Cleak=0.069		n=0.65
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	3,20 W/m2
Hot water flow (constant)	0,0159 l/s

4f: Q50=0.6, H2 (additional insulation partial demolition), balanced vent, attic insulation

Building envelope

Load bearing wall

150	concrete
200	mineral wool
200	mineral wool + studs
30	air gap
22	brick screen

Infill wall

13	foliated gypsum board
120	mineral wool +studs
100	mineral wool
200	mineral wool + studs
30	air gap
22	brick screen

Ground

	plastic mat
50	concrete
60	sand
30	mineral wool
180	concrete

Roof

150	concrete
420	cellulose insulation

Windows

U_{pane}=0,5 [W/(m^2·K)]

U_{frame}=1,1 [W/(m^2·K)]

Ψ_{spacer}=0,027 [W/(m·K)]

SHGC=0,6916 [-]

T=0,5776 [-]

Air tightness

q_{50}=0,6 [l/m$^{2\cdot}$s]

Thermal Bridges

K_{bridge}=31 [W/K]

Ventilation

Flow			0,35l/m^2
HEX			η=0,8
supply air set point temperature			17°C
temperature rise in vent system			1°C
Cventholes=0	Cleak=0.069		n=0.65
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	3,20 W/m2
Hot water flow (constant)	0,0159 l/s

5a: Q50=0.6, original wall, balanced vent, attic insulation, hot water reduction, electricity reduction

Building envelope

Load bearing wall

150	concrete
100	mineral wool
30	air gap
60	bricks

Infill wall

13	foliated gypsum board
120	wooden studs+mineral wool
30	mineral wool
120	bricks

Ground

	floor sheeting
80	insulation panels λ=0,023
180	concrete

Roof

150	concrete
420	blown mineral wool

Windows

U_{pane}=0,5 [W/(m^2·K)]

U_{frame}=1,1 [W/(m^2·K)]

Ψ_{spacer}=0,027 [W/(m·K)]

SHGC=0,6916 [-]

T=0,5776 [-]

Air tightness

q_{50}=0,3 [l/m$^{2\cdot}$s]

Thermal Bridges

K_{bridge}=79 [W/K]

Ventilation

Flow			0,35l/m^2
HEX			η=0,8
supply air set point temperature			17°C
temperature rise in vent system			1°C
Cventholes=0	Cleak=0.069		n=0.65
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C	
Equipment	3,20 W/m2	
Hot water flow (constant)	0,0159 l/s	flow reductive nozzels

5b: Q50=0.6, L1 (additional insulation no demolition), balanced vent, attic insulation, hot water reduction, electricity reduction

Building envelope

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	wooden studs+mineral wool
30	blown mineral fibres	30	mineral wool
60	bricks	120	bricks
70	mineral wool + studs	70	mineral wool + studs
30	air gap	30	air gap
22	brick screen	22	brick screen

Ground		*Roof*	
	floor sheeting	150	concrete
80	insulation panels λ=0,023	420	blown mineral wool
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=0,5 [W/(m^2·K)]	q_{50}=0,3 [l/m^{2}·s]	K_{bridge}=34 [W/K]
U_{frame}=1,1 [W/(m^2·K)]		
Ψ_{spacer}=0,027 [W/(m·K)]		
SHGC=0,6916 [-]		
T=0,5776 [-]		

Ventilation

Flow			0,35l/m^2
HEX			η=0,8
supply air set point temperature			17°C
temperature rise in vent system			1°C
Cventholes=0	Cleak=0.069		n=0.65
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	3,20 W/m2
Hot water flow (constant)	0,0159 l/s

5c: Q50=0.6, I1 (additional insulation no demolition), balanced vent, attic insulation, hot water reduction, electricity reduction

Building envelope 10

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	wooden studs+mineral wool
30	blown mineral fibres	30	mineral wool
60	bricks	120	bricks
170	mineral wool + studs	170	mineral wool + studs
30	air gap	30	air gap
22	brick screen	22	brick screen

Ground		*Roof*	
	floor sheeting	150	concrete
80	insulation panels λ=0,023	420	blown mineral wool
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=0,5 [W/(m^2·K)]	q_{50}=0,3 [l/m^2·s]	K_{bridge}=34 [W/K]
U_{frame}=1,1 [W/(m^2·K)]		
Ψ_{spacer}=0,027 [W/(m·K)]		
SHGC=0,6916 [-]		
T=0,5776 [-]		

Ventilation

Flow			0,35l/m^2
HEX			η=0,8
supply air set point temperature			17°C
temperature rise in vent system			1°C
Cventholes=0	Cleak=0.069		n=0.65
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	3,20 W/m2
Hot water flow (constant)	0,0159 l/s

5d: Q50=0.6, H1 (additional insulation no demolition), balanced vent, attic insulation

Building envelope 10

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	wooden studs+mineral wool
30	blown mineral fibres	30	mineral wool
60	bricks	120	bricks
100	mineral wool	100	mineral wool
170	mineral wool + studs	170	mineral wool + studs
30	air gap	30	air gap
22	brick screen	22	brick screen

Ground		*Roof*	
	floor sheeting	150	concrete
80	insulation panels λ=0,023	420	cellulose insulation
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=0,5 [W/(m^2·K)]	q_{50}=0,3 [l/m^2·s]	K_{bridge}=31 [W/K]
U_{frame}=1,1 [W/(m^2·K)]		
Ψ_{spacer}=0,027 [W/(m·K)]		
SHGC=0,6916 [-]		
T=0,5776 [-]		

Ventilation

Flow			0,35l/m^2
HEX			η=0,8
supply air set point temperature			17°C
temperature rise in vent system			1°C
Cventholes=0	Cleak=0.069		n=0.65
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	3,20 W/m2
Hot water flow (constant)	0,0159 l/s

5e: Q50=0.6, I2 (additional insulation partial demolition), balanced vent, attic insulation

Building envelope

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
100	mineral wool	120	mineral wool +studs
200	mineral wool + studs	200	mineral wool + studs
30	air gap	30	air gap
22	brick screen	22	brick screen

Ground		*Roof*	
	floor sheeting	150	concrete
80	insulation panels λ=0,023	420	cellulose insulation
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=0,5 [W/(m^2·K)]	q_{50}=0,3 [l/m^2·s]	K_{bridge}=31 [W/K]
U_{frame}=1,1 [W/(m^2·K)]		
Ψ_{spacer}=0,027 [W/(m·K)]		
SHGC=0,6916 [-]		
T=0,5776 [-]		

Ventilation

Flow			0,35l/m^2
HEX			η=0,8
supply air set point temperature			17°C
temperature rise in vent system			1°C
Cventholes=0	Cleak=0.069		n=0.65
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	3,20 W/m2
Hot water flow (constant)	0,0159 l/s

5f: Q50=0.6, H2 (additional insulation partial demolition), balanced vent, attic insulation

Building envelope

Load bearing wall		*Infill wall*	
150	concrete	13	foliated gypsum board
200	mineral wool	120	mineral wool +studs
200	mineral wool + studs	100	mineral wool
30	air gap	200	mineral wool + studs
22	brick screen	30	air gap
		22	brick screen

Ground		*Roof*	
	floor sheeting	150	concrete
80	insulation panels λ=0,023	420	cellulose insulation
180	concrete		

Windows	*Air tightness*	*Thermal Bridges*
U_{pane}=0,5 [W/(m^2·K)]	q_{50}=0,3 [l/m^2·s]	K_{bridge}=31 [W/K]
U_{frame}=1,1 [W/(m^2·K)]		
Ψ_{spacer}=0,027 [W/(m·K)]		
SHGC=0,6916 [-]		
T=0,5776 [-]		

Ventilation

Flow			0,35l/m^2
HEX			η=0,8
supply air set point temperature			17°C
temperature rise in vent system			1°C
Cventholes=0	Cleak=0.069		n=0.65
	ΔP	*η*	
Supply fan	800	0,6	
Exhaust fan	500	0,6	

Indoor and residents parameters

Indoor air temperature	22°C
Equipment	3,20 W/m2
Hot water flow (constant)	0,0159 l/s