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A parametric study using numerical simulations

Master's thesis in Structural Engineering and Building Technology

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Cover:
Photo of Brämaregatan 1 as original, after first renovation and after second renovation (Photo: BRF Brämaregatan).

Chalmers Reproservice
Gothenburg, Sweden 2017

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Abstract

During 1975-2002, 50 % of the Swedish multi-family buildings from before 1945 was renovated. A large part of these buildings are now facing a second renovation as the renovation measures are reaching the end of their service life. In order to identify further possibilities for increased energy efficiency in connection with a second renovation, a detailed investigation of the energy use has been made in one of these buildings.

The thesis aims to identify the parameters that have the greatest effect on energy use in a renovated multi-family building from before 1945. The results are also generalized to be applicable on buildings similar to the studied building in order to find best measures for increased energy efficiency. Simulations with a parameter study was chosen as the method for reaching the aim.

A renovated "Landshövdingehus" from 1910 was chosen as the case study for simulations. The major part of the building consists of apartments, but there are also restaurants and storage areas on the ground floor. The building was simulated in its current state but also as a 100 % residential building, the later case is referred to as the "normalised" building. The parameter study, including measures for decreased energy use, was performed on the normalised building.

A comparison between the current and normalised building showed that transmission losses becomes more dominant when changing the activities from restaurants/storage to apartments. This is due to a combination of higher indoor temperatures and lower ventilation rates. A main observation from the comparison is that the activities inside the building has a large influence on the magnitude of the losses. The parameter study showed that the best measures to reduce energy use are to install a ventilation system with a heat exchanger, insulate the outer walls of the ground floor and replace old windows.

General conclusions about "Landshövdingehus" are that the ground floors can account for a large use of energy compared to the other floors. Indications of energy inefficient ground floors are uninsulated brick walls and large old display windows. The ground slab is also unfavourable for the ground floor as it was not originally insulated in these type of buildings.

Keywords: Renovation, Old buildings, Energy use, Energy renovation

Energianvändning i ett om-renoverat flerbostadshus från 1910
En parameterstudie baserat på numeriska simuleringar
Examensarbete inom Structural Engineering and Building Technology
GUSTAV THURESSON
Instutionen för Bygg- och Miljöteknik
Avdelningen för Byggnadsteknologi
Byggnadsfysikalisk modellering
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SAMMANFATTNING

Under 1975-2002 renoverades 50 % av det Svenska flerbostadsbeståndet. Renoveringsåtgärderna börjar nu lida mot slutet av sin livslängd och en stor del av byggnaderna står därför inför en andra renovering. För att öka energieffektiviseringen i samband med en andra renovering krävs det en detaljerad kartläggning av energianvändningen i ett tidigare renoverat äldre flerbostadshus.

Syftet med examensarbetet är således att identifiera de parametrar som har störst inverkan på energiförbrukningen i ett renoverat flerfamiljshus byggt innan 1945. Resultaten skall även generaliseras till att vara applicerbara på byggnader liknande den som studerats. Baserat på detta skall förslag ges på de bäst lämpade åtgärderna för ökad energi effektivitet. För att undersöka byggnadens energianvändning samt göra parameterstudier används numeriska simuleringar i kombination med ritningsgranskning och studiebesök.

Ett renoverat landshövdingehus från 1910 har valts till att ligga som grund för simuleringarna. Majoriteten av husets yta upptas av lägenheter, men det finns även restauranger och lager på bottenvåningen. Byggnaden har simulerats i sitt nuvarande skick men också som ett renodlat lägenhetshus, där det senare av de två fallen benämns som ”normaliserat”. Parameterstudien, innehållande åtgärder för minskad energianvändning, är utförd på den normaliserade byggnaden.

Jämförelsen mellan den nuvarande och normaliserade byggnaden visar att transmissionsförluster blir mer dominanta när verksamheten i byggnaden ändras från restaurang/lager till lägenheter. Anledningen är en kombination av högre inomhustemperatur och färre luftomsättningar. Parameterstudien visade att de bästa åtgärderna för att minska energianvändningen är installation av ventilationssystem med värmeväxlare, isolera bottenvåningens ytterväggar och ersätta äldre fönster.

Generella slutsatser om landshövdingehus är att bottenvåningen kan stå till svars för stor energianvändning jämfört med de andra våningsplanen. Tecken på att så är fallet är oisolerade tegelväggar och stora äldre skyltfönster. Bottenplattan spelar också in, då den ej isolerades under byggnation eller renovering.

Nyckelord: Renovering, Äldre byggnader, Landshövdingehus, Energianvändning, Energirenovering

CONTENTS

PREFACE

This thesis is a part of the project *Re-renovation: Possibilities for increased energy efficiency and the re-creation of cultural historical values*, financed by Swedish Energy Agency's Programme Save & Preserve. The work was supervised by Pär Johansson, assistant professor and Paula Wahlgren, associate professor.

I would like to give a special thanks to Pär Johansson and Paula Wahlghren for constant feedback and engagement throughout the project. I would also like to thank Angela Sasic and Hans Wetterlund, WSP for valuable inputs regarding input data and simulation, Joris van Rooij at Göteborg Energi for providing energy data, John Nyström, Erika Fryklind and William Karlsson for inviting us into their apartments and providing valuable information.

I would finally like to thank Fikagruppen for high quality entertainment throughout the thesis work.

Göteborg June 2017
Gustav Thuresson

Nomenclature

Greek capital letters

ΔT temperature difference (K)
ΣT summation (-)

Greek lower case letters

ϕ angle of incidence (°)
ρ_a density (kg/m^3)
ρ_a density of air (kg/m^3)
τ_D windows transmittance of direct solar radiation (-)
τ_d windows transmittance of diffuse solar radiation (-)
φ addition for thermal bridges (-)

Roman lower case letters

c_{pa} specific heat capacity of air (J/(kg K))
c_p specific heat capacity (J/(kg K))
d thickness(m)

Roman capital letters

A area (m^2)
A_w window area (m^2)
$A_{envelope}$ area of the building envelope (m^2)
C thermal heat capacity (J/K)
I_D direct solar radiation (W/m^2)
I_d diffuse solar radiation (W/m^2)
K_{tot} total thermal conductance (W/K)
P thermal conductance of the heating system (W/K)
Q_{el} heat gain from electricity (W)
Q_{gas} heat gain from use of gas stove (W)
$Q_{heating}$ heat gain from radiators (W)
Q_{int} heat gain from internal gains (W)
$Q_{leakage}$ heat loss due to air leakages in the thermal envelope (W)
Q_{people} heat gain from people (W)
Q_{solar} heat gain due to solar radiation through windows (W)
Q_{trans} heat loss due to transmission (W)
Q_{tw} heat gain from use of tap water (W)
Q_{vent} heat loss due to ventilation (W)
R_a airflow through the building envelope (m^3/s)
$R_{a,4}$ airflow through leakages in the building envelope at the pressure difference 4 Pa (m^3/(s m^2))

$R_{a,50}$	airflow through leakages in the building envelope at the pressure difference 50 Pa ($m^3/(s\,m^2)$)
T_{in}	indoor temperature (K)
T_{target}	set point indoor temperature (K)
U	thermal transmittance ($W\,m^2/K$)
W_s	shading coefficient (-)

1 Introduction

A significant part of the older multi-family buildings require modernization and renovation within the next couple of years. Many of these buildings have already been renovated and hence the next renovation will be their second one. There is an ongoing project at the Department of Architecture and Civil Engineering at Chalmers University of Technology which aims to develop guidelines for the renovation and re-renovation (second renovation) of buildings built before 1945. The guidelines should consider cultural value, modern standards of functionality and energy efficiency. This thesis is mainly focusing on energy efficiency, but will still consider historical values and modern standards.

So far in the project, a qualitative study of around 600-700 dwellings in Gothenburg have been made, including energy use and site visits with investigation of e.g. degree of renovation. The correlation between energy efficiency and degree of renovation is remarkably small (Johansson, Wahlgren, Femenías, Thuvander, and Mörk, 2017). In order to identify further possibilities for increased energy efficiency in connection with a re-renovation, there is a requirement for detailed investigation of the energy use in a renovated building from before 1945.

1.1 Aim

The main aim of the work is to identify the parameters that have the greatest effect on energy use in a renovated multi-family building from before 1945. The results are also generalized to be applicable on buildings similar to the studied building in order to find the best measures for increased energy efficiency.

1.2 Methodology

The first step was to find a building that matches the purpose of the thesis. The owners of several buildings were contacted. Based on the amount of data available, the history of the building and interest from the owners, Brämaregården 1 was chosen.

Next, information was gathered about the chosen building. This was done by studying drawings, reading public documents of renovation measures, talking with the owners and performing a study visit. The study visit included thermal photography, measurements of visible construction parts, notes of surface materials and measurement of indoor temperatures. All information gathered was used for building a database over the building design and materials. In case data of construction parts were missing, assumptions were made based on literature of typical construction methods for buildings from the same era.

Most soft parameters, as internal gains and indoor temperatures, were treated as suggested in Levin (2012a). Where information has been lacking and sources insufficient, input data has been based on reasoning. The data of electricity use and use of district heating was provided by Göteborg Energi. In order to control input data and assumptions, a meeting was arranged with Hans Wetterlund, an energy simulation expert at WSP.

Weather data was collected from SMHI. In case data was not available for Gothenburg, data from the station closest to Gothenburg was used. The data for solar radiation was post-processed in Matlab in order separate the global radiation into diffuse and direct. Simulations were chosen as the method to evaluate which parameters that have the largest effect on the energy use. Weather data together with the rest of the input data was used to simulate the building. The programs used for simulations were Simulink and Matlab. The model was calibrated and verified against the data on the use of district heating from Göteborg Energi.

As a method of find the impact of the activities and operations on the energy use, the building was remodelled to only contain apartments. This was denoted as "normalising" the building. A comparison was then made between the original and normalised building. In order to investigate measures for increased energy efficiency a parameter study were performed. The parameters studied was decided based on the results from the normalised building.

1.3 Limitations

The study is performed on one building only. The simulations are limited to Gothenburg climate as the building studied is situated in Gothenburg. The weather data is from 2016.

No cost estimations are performed for the measures tested as the thesis is mainly focused on were there is potential to save energy. The measures tested are also limited to address the energy needed for heating the building. The results from energy simulations are not compared to guideline values or energy declarations and hence no regards have been taken in how the weather of 2016 differs from a normal year.

2 Modelled building - Brämaregatan 1

The building is placed centrally in the town of Gothenburg, on the adress Brämaregatan 1. The building is situated on a corner with one of the short sides in direct connection with another building, see Figure 2.1.

Figure 2.1: The figure shows how the building is located in relation with its direct surroundings ENIRO(2017) (left) and the view from the street (right).

In this chapter the building is described and investigated with respect to the thermal performance. First the technical aspects of the building are described, which includes, materials, areas, U-values, ventilation system, heating system etc. Second the building's history is looked into. Finally, a technical assessment is made. The technical assessment is mainly based on the field visit where parts of the building were inspected with thermal camera.

2.1 Operations and plan views

Today the building is used for several different activities. On the ground floor there are two restaurants, two storage areas and laundry room. Most of the storage area is occupies by a company that is using it for storing household appliances. The two middle storeys (two and three) are only occupied by apartments. There are eight apartments on each floor. The top floor (attic floor) is also used for residential purposes holding five apartments. There is also a basement under one small part of the building. It consists of storage areas and a furnace. Table 2.1 shows the area for the different storeys and activities.

Table 2.1: Overview of the buildings area division.

Floor	Activity	Area (m^2)
Basement	Storage	100
First	Restaurants	243
First	Storage	171
Second	Apartments	410
Third	Apartments	410
Attic	Apartments	370
All	Staircases	42

The plan view of the ground floor is shown in Figure 2.2. The common laundry room is to the upper left, all remaining non marked areas are staircases. The basement is situated in the left part of the building, under the smaller restaurant. A detailed plan view of the larger restaurant is shown in Figure 2.3. Notice the position of the entrance, kitchen fan and dining room as this is of importance later on. The plan view of storey two and three can be seen in Figure 2.5 and the plan view of the attic in Figure 2.4.

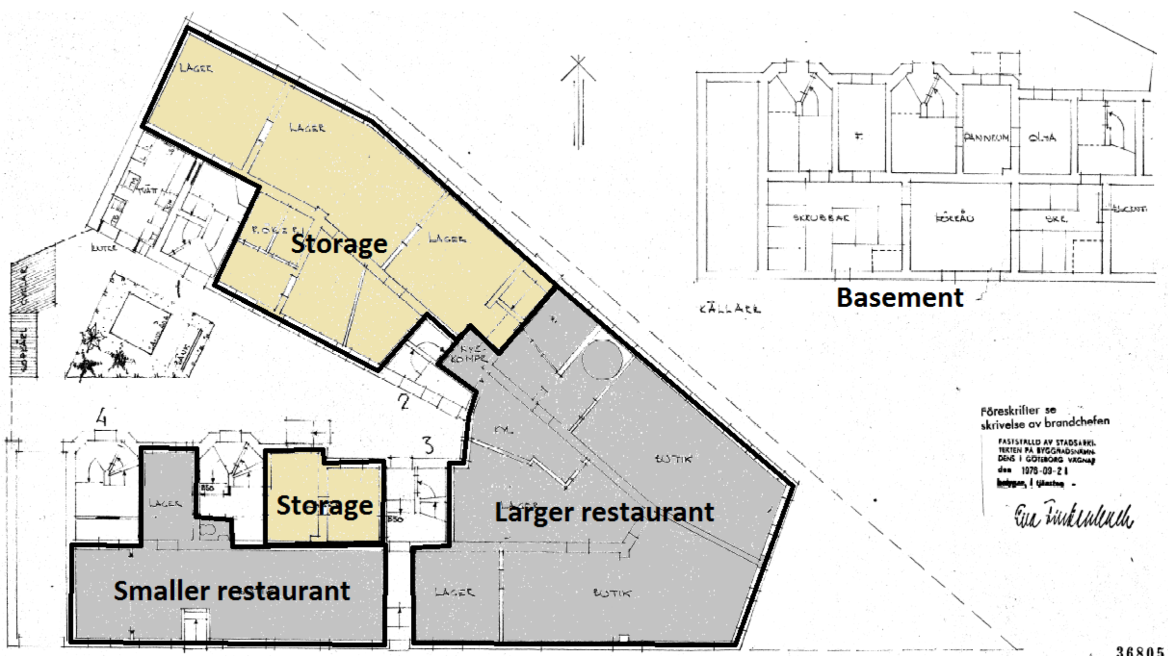


Figure 2.2: Plan view of the entrance floor and basement.

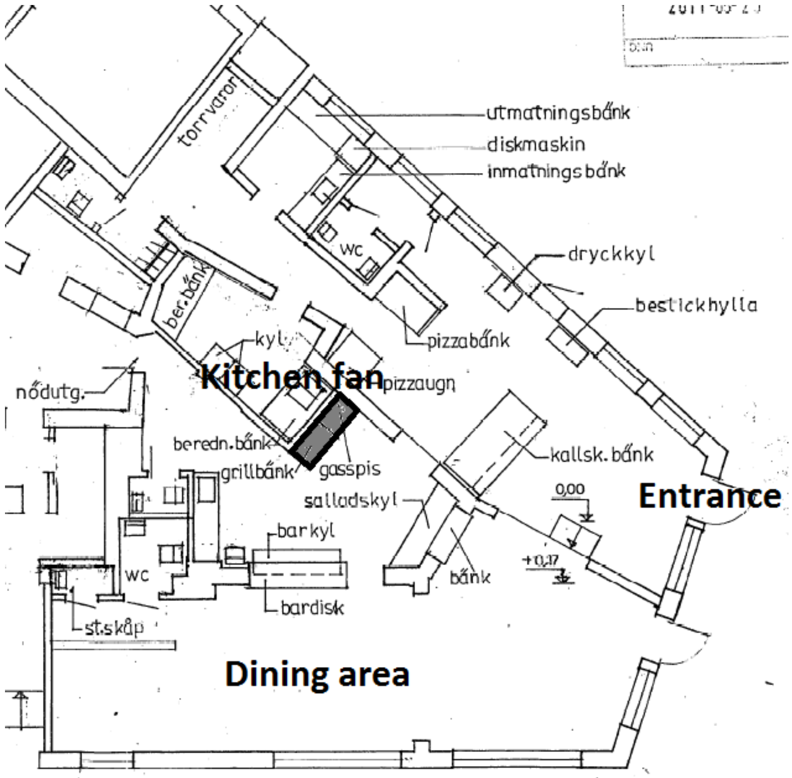


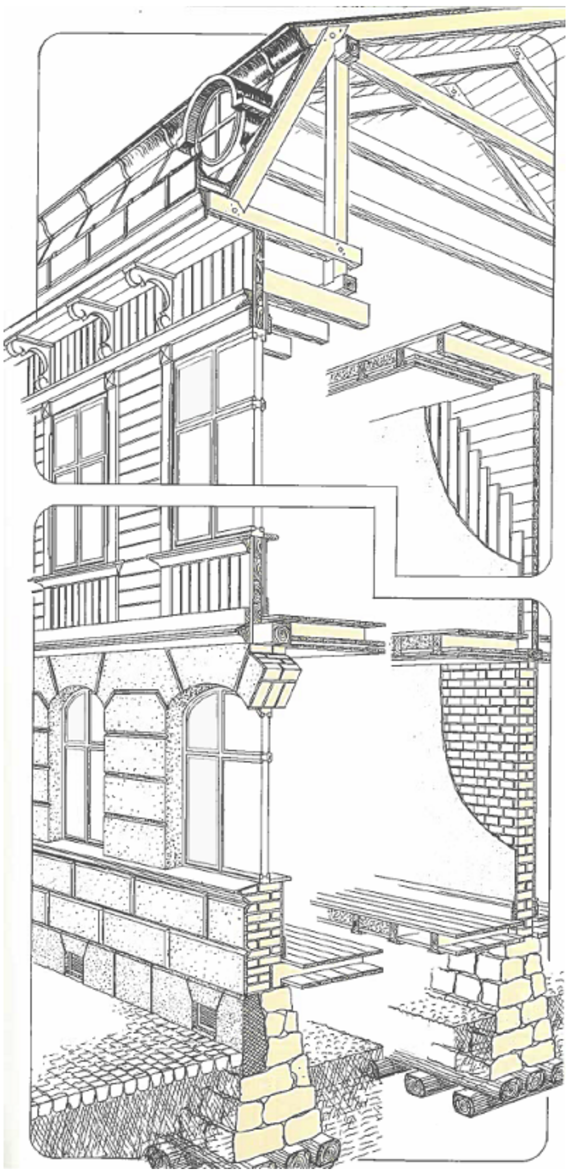
Figure 2.3: Detailed plan view of larger restaurant.

Figure 2.4: Plan view of the attic apartments.

Figure 2.5: Plan view of second and third floor.

2.2 Construction

In this section the different building parts are presented together with the source of information. The building parts described in this section lays the foundation to the simulation model. For a complete list of building parts, see Appendix A.



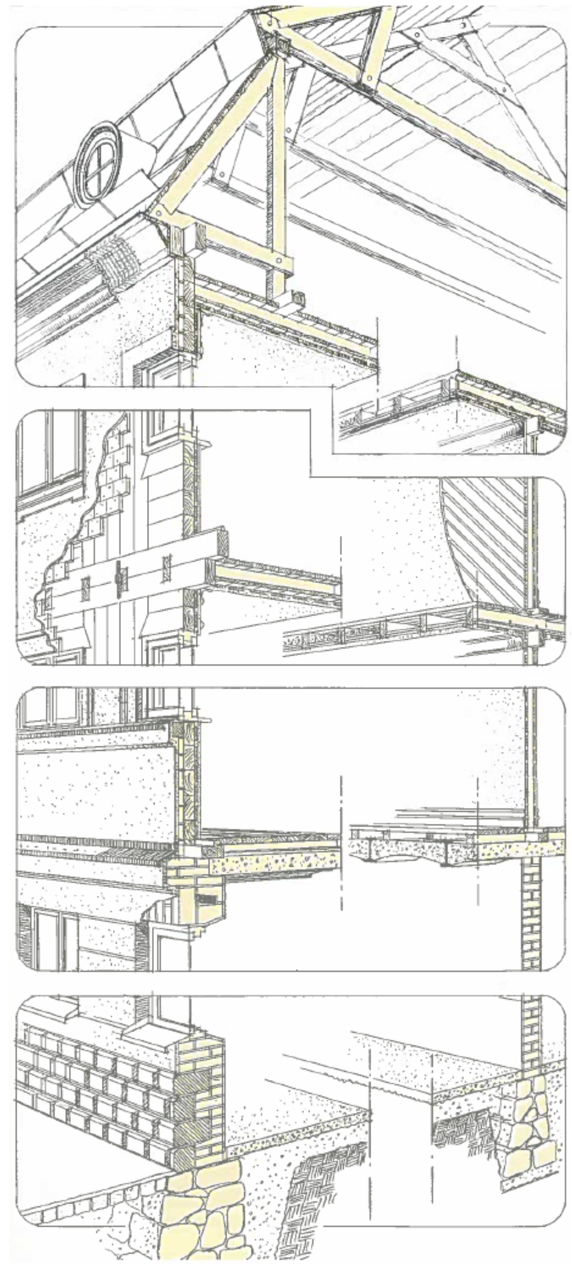


Figure 2.6: Two typical constructions of "Landshövdingehus". The left was mainly used between 1890-1900, the right between 1900-1910. The pictures are taken from Björk, Kallstenius, and Reppen, 1983.

The house has the typical construction of a "Landshövdingehus". The ground floor is constructed in brick and the upper floors are in wood. Two examples of this type of construction can bee seen in Figure 2.6. Figure 2.6 (left) shows the older construction method of the two. All floor structures between storeys are made of wood and there is a crawl space beneath the ground floor. Figure 2.6 (right) shows a more modern construction method, where a concrete slab is placed on the ground and the floor structure of the second storey is made of concrete. For the modern method the wooden façade is covered in rendering on both sides. Brämaregården 1 has influences from both examples.

2.2.1 Ground floor

Table 2.2 shows all building parts used in the ground floor with estimated U-values. The U-value calculations are based on standard thermal conductivity's for the materials included in each building part. Surface resistances are also included in calculations.

Table 2.2: Description of building parts used in entrance floor.

Part	Layer of insulation (mm)	Insulation material	U-value ($W/(m^2\,K)$)	Area (m^2)
Ground slab	0	-	0.57	320
Outer walls	0	-	1.5	421
Floor structure over basement	150	Sawdust	0.40	95
Windows	-	Single-pane	5.5	67
Windows	-	Double-pane	2.5	22

The building is founded on piles of grey-stone which in turn is resting on wooden poles. See Figure 2.7 for orientation. As stated earlier there is a basement under one part of the building while the other part is estimates to have a concrete slab resting on a layer of crushed stone. The basement have a concrete floor and brick walls, it is not heated. The slab part of the building is similar to Figure 2.6 (right) as there is no crawl space beneath the building. The U-value for the slab is estimated according to the method presented in Petersson (2009), section 9.2.5. The outer walls of the ground floor are made of brick only and are 30 cm thick. The thermal conductivity of brick is 0.6 W/(m K) (Hagentoft, 2001).

From observation, it appears that most of the restaurant windows only consists of one single glass. For U-value calculations, these windows have been treated as glass sheets with surface resistances. The storage windows have double glass layers. The U-value for the double-pane windows have been taken from Olsson-Jonsson and Ekstrand-Tobin (2011). The floor structures are made out of wood with sawdust as insulating material. They are estimated to have the same properties throughout the building. The thermal conductivity of sawdust is set to 0.08 W/(m K) (Bokalders, 2011).

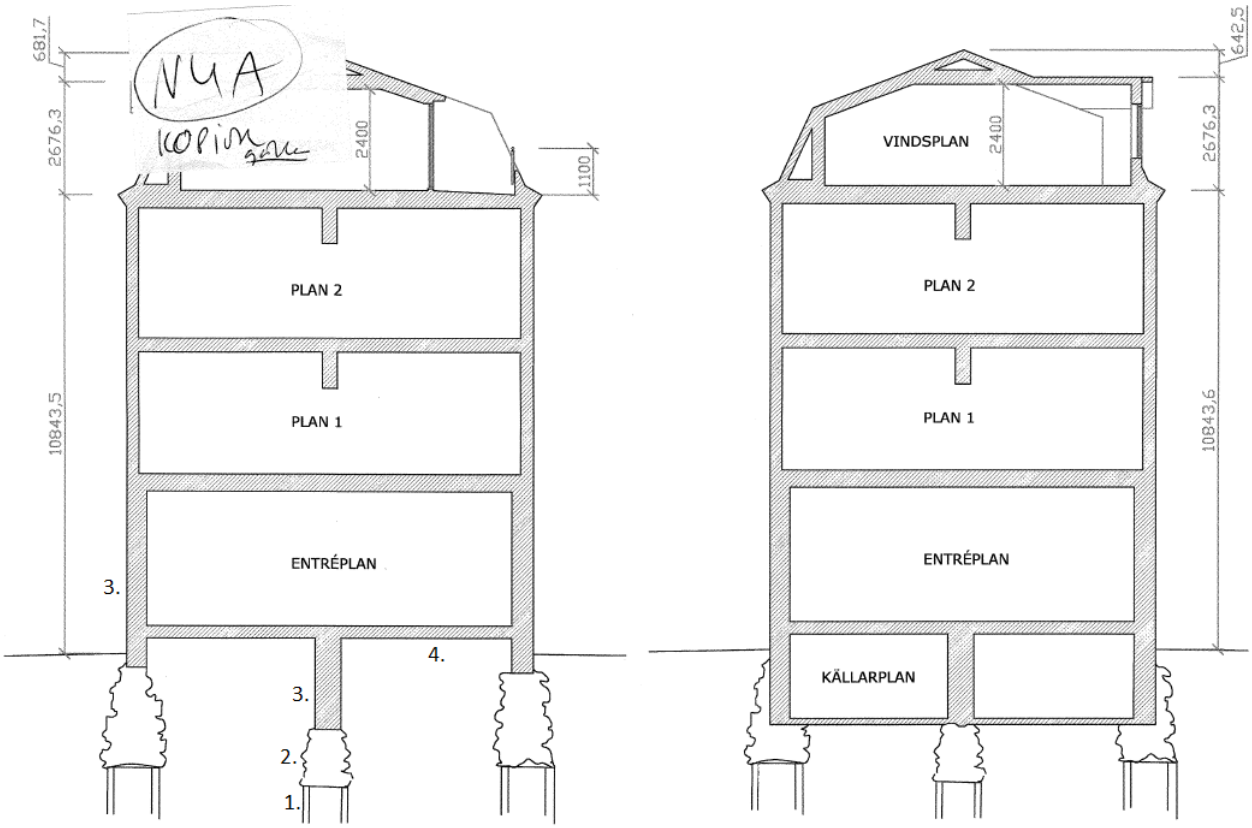


Figure 2.7: Section view of Brämaregatan 1. Explanation to numbers: 1. Wooden poles, 2. Pile of grey-stone, 3. Brick wall, 4. Concrete ground slab.

2.2.2 Second and third floor

The second and third floor have similar properties. Table 2.3 shows all building parts used on the second and third floor.

Table 2.3: Description of building parts used in second and third floor.

Part	Layer of insulation (mm)	Insulation material	U-value (W/(m^2 K))	Area (m^2)
Outer walls - street	100	Unknown	0.26	508
Outer walls - yard	50	Mineral wool	0.42	349
Flooring 2nd floor	150	Sawdust	0.40	410
Flooring 3rd floor	150	Sawdust	0.40	410
Windows	Double-pane	-	2.5	32
Windows	Triple-pane	-	1.3	129

The outer walls are originally made out of wood with a similar construction to the one seen in Figure 2.6

(left). The original construction is still in place, but extra insulation have been added on the outside, 100 mm towards the street and 50 mm towards the inner yard. The two different façades can be seen in Figure 2.8. A cross section of the outer wall towards the street is shown in Figure 2.9. The thermal conductivity of the insulation have been approximated to 0.037 W/(m K). There are two different types of windows as well, triple-pane windows towards the street and double-pane windows towards the yard. The U-value for both windows are taken from Olsson-Jonsson and Ekstrand-Tobin (2011).

Figure 2.8: Left: The view from the street. Right: View from the yard.

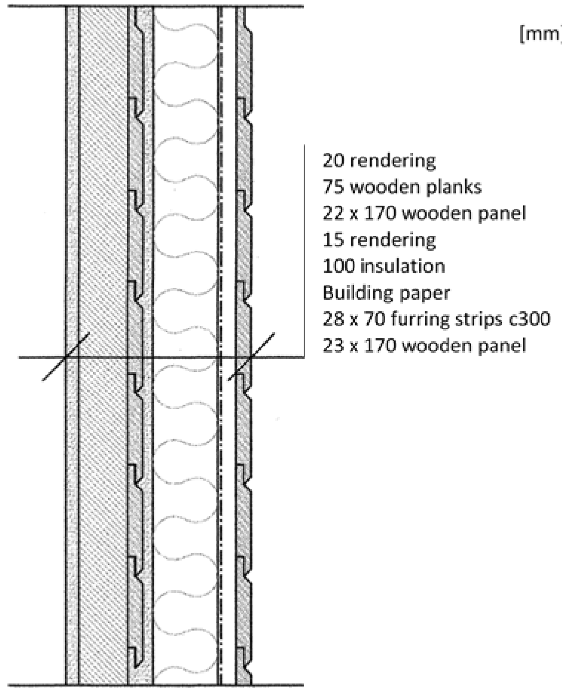


Figure 2.9: The outer wall towards the street, indoors is to the left, outdoors to the right.

2.2.3 Attic

Table 2.4 shows all building parts used in the attic. The attic is enveloped by the the roof, which mainly has two different inclinations. Close to the walls the inclination is steep. In Table 2.4 this area is described as the walls. In the middle of the building the inclination is not as steep, this is described as the roof.

Table 2.4: Description of building parts used in the attic.

Part	Layer of insulation (mm)	Insulation material	U-value (W/(m^2 K))	Area (m^2)
Outer walls	195	Unknown	0.17	177
Roof	195	Unknown	0.17	432
Flooring	200	Unknown	0.14	370
Windows	Triple-pane	-	1.9	42

The roof and walls of the attic, together with the materials used can be distinguished in Figure 2.10. The floor structure differs from the rest of the building by having extra insulation. The thermal conductivity of the extra insulation has been approximated to 0.037 W/(m K). The windows of the attic are of the same kind as the triple-pane windows in the third and second floor.

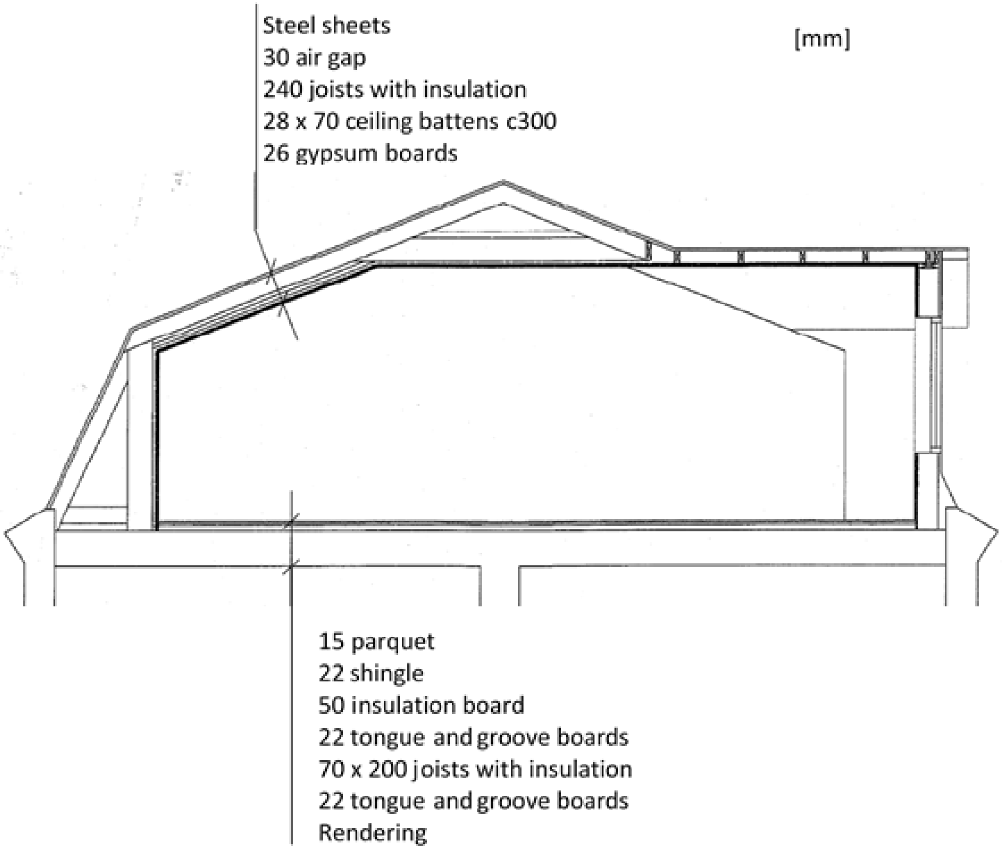


Figure 2.10: Section of the attic. The two main inclinations of the roof is shown in the figure. There are also horizontal parts in connection with the terraces.

2.3 Ventilation and heating

The whole building has mechanical exhaust air ventilation. In the apartments, supply air enters through openings placed over the windows. For the entrance floor there are inlets placed in the brick façade. Each of the attic apartments has an own exhaust air fan. There is no documentation of how many exhaust fans there are for each apartment on the second and third floor. The smaller restaurant has an own exhaust air duct connected to a fan on the roof. The larger restaurant uses a kitchen fan as well as mechanical exhaust ventilation. There is no documentation of any heat recovery system in the building. The building uses district heating connected to a radiator system.

2.4 History

The property was originally built in two stages. The first part was built 1910. The second part was added 1915 and it is under this part the basement is situated. From the beginning, the outer wall appearance was very similar to the ones seen in Figure 2.6. The first storey had the same brick walls that can be seen today. The walls of the second and third storey had 22 mm thick wooden panels as exterior, 75 mm x

225 mm horizontally placed planks as load bearing core and 20 mm of rendering as interior. There were most likely tile stoves providing heat to the building. The attic was unfurnished and unheated.

In 1936 water closets were installed in the building. On The same drawings describing the installation of water closets, a boiler room is defined in the basement. In 1944 the outer brick façade was updated with new larger windows and in 1965 an electric boiler was installed.

2.4.1 First renovation - 1975

In 1975 the building was renovated. The wooden outer walls was complemented with 50 mm mineral wool and a yellow sheet metal façade (See Figure 2.11b). The windows of storey two and three were changed to double-pane. The existing ventilation ducts were cleaned and caulked for reuse. Exhaust fans were installed on the attic for extraction of air from kitchens and sanitary areas.

Inside the apartments, all apartment dividing walls were complemented with 75 mm wooden studs, mineral wool and particle boards. A dense wood fibre board and a plastic carpet were added to floors and all interior walls were covered in wallpaper. The basement was left in existing conditions. Figure 2.11 shows the looks before and after the first renovation.

Figure 2.11: Building before and after first renovation.

2.4.2 Second renovation - 2010

During this renovation the attic was turned into apartments. There was 195 mm of insulation added to the roof and 50 mm insulation boards were added to the attic floor (see Figure 2.10). The exhaust fans situated in the attic were placed upon the roof and new ones were installed for the new apartments. Radiators were installed in the attic and connected to the existing heating system.

Another 50 mm of insulation was added to the outer wall facing the street and the metal sheeting was replaced by wooden panels (see Figure 2.1b and Figure 2.9). The windows towards the street were changed to 3-glass. Windows were also added to the side of the roof. The outer wall and the windows towards the yard remained untouched.

2.5 Technical assessment

An assessment was made of the house from a building physical point of view. The assessment is mainly based on drawings and thermal images from the field visit. Two apartments were visited during the field visit. One attic apartment and one apartment on the third floor. A visit was also made at the larger restaurant, but no thermal images were taken. The outdoor temperature was 4.4 °C during the field visit. It had been raining during the night and the sky was cloudy. Images were taken between 7:00 and 8:00 in the morning. Note that the temperature interval is not the same for all figures.

2.5.1 Attic apartment

The average measured indoor temperature was approximately 22 °C, varying between 21.2 °C and 22.9 °C depending on location in the apartment. There are no visible thermal bridges of studs in the roof of the attic apartments. There are some thermal bridges around joints to the roof windows (Figure 2.12) and the cold air entering over the window is also visible. It is in general colder around all corners of the roof (Figure 2.13). There is also a temperature drop in the connection between the inner wall and the attic floor, next to the dishwasher (Figure 2.14).

Figure 2.12: Infrared photo of attic window. Temperature scale in Celsius.

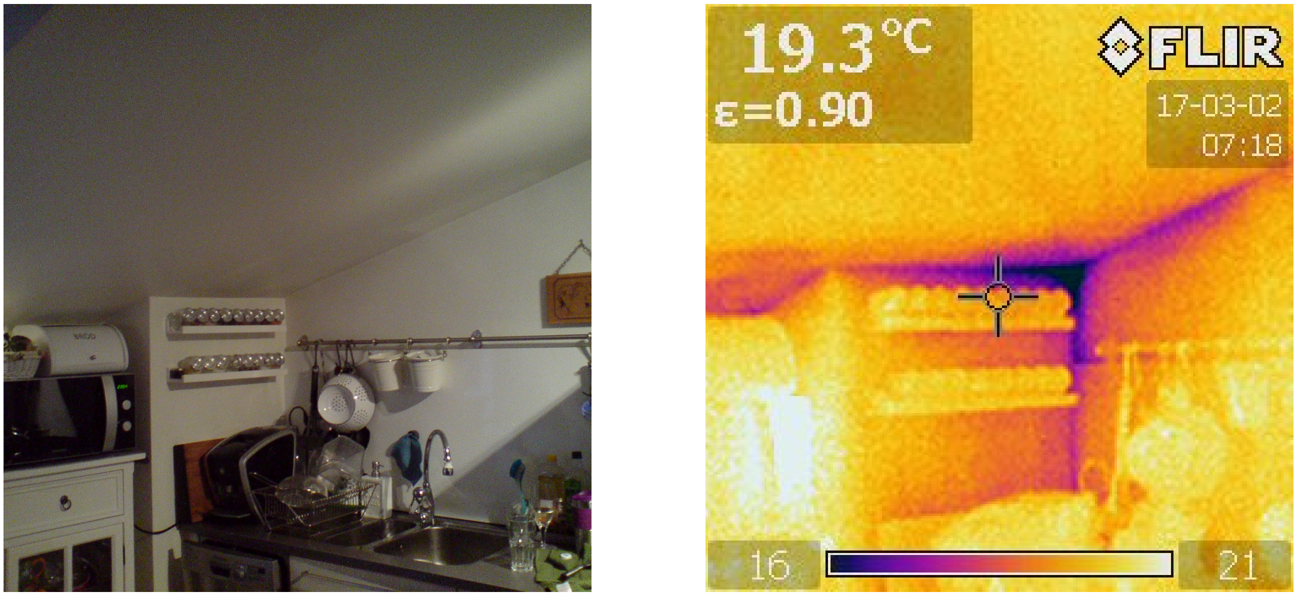


Figure 2.13: Infrared photo of attic roof corner. Temperature scale in Celsius.

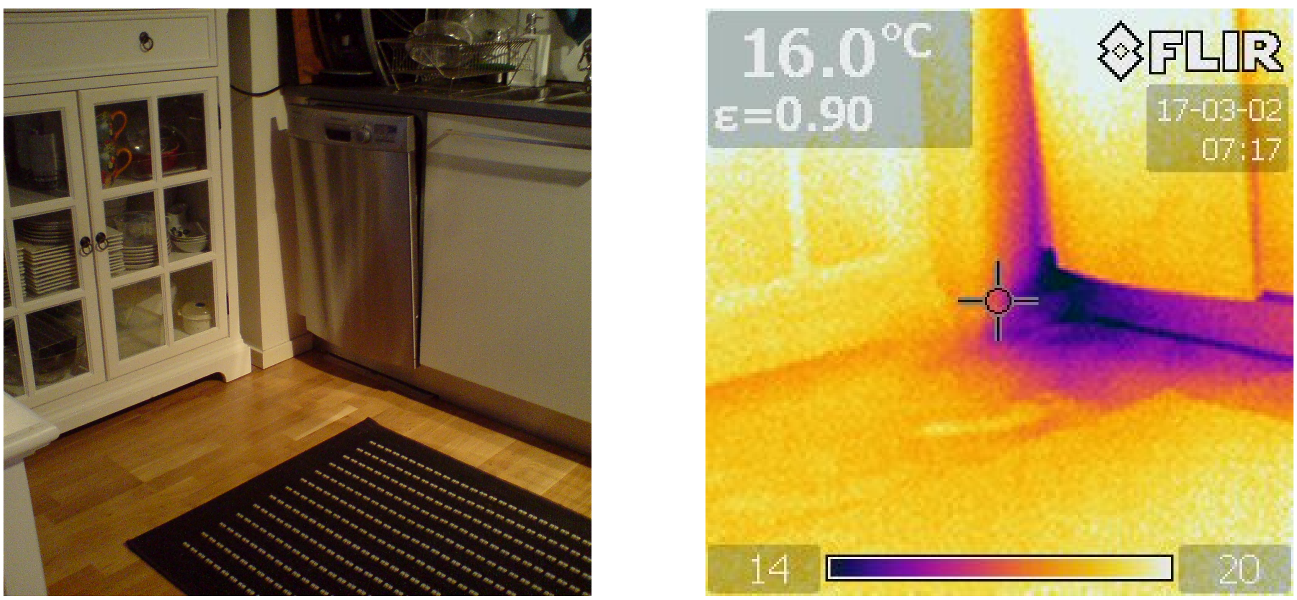


Figure 2.14: Infrared photo of attic inner wall to floor connection. Temperature scale in Celsius.

2.5.2 Third floor apartment

The average measured indoor temperature was again approximately 22 °C. The air inlets over the windows are highly visible on the thermal camera (Figure 2.15). As for the attic, temperatures were lower in corners (Figure 2.16). Former ventilation openings had not been properly insulated. This can be seen in Figure 2.17.

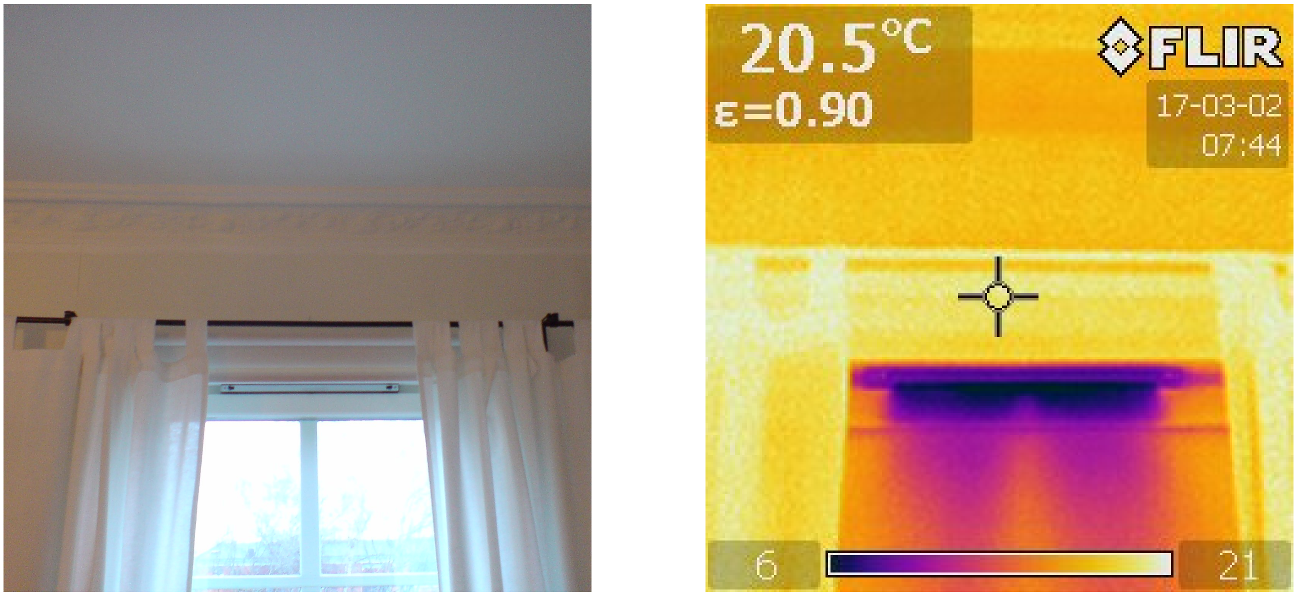


Figure 2.15: Infrared photo of ventilation over window in the third floor apartment. Temperature scale in Celsius.

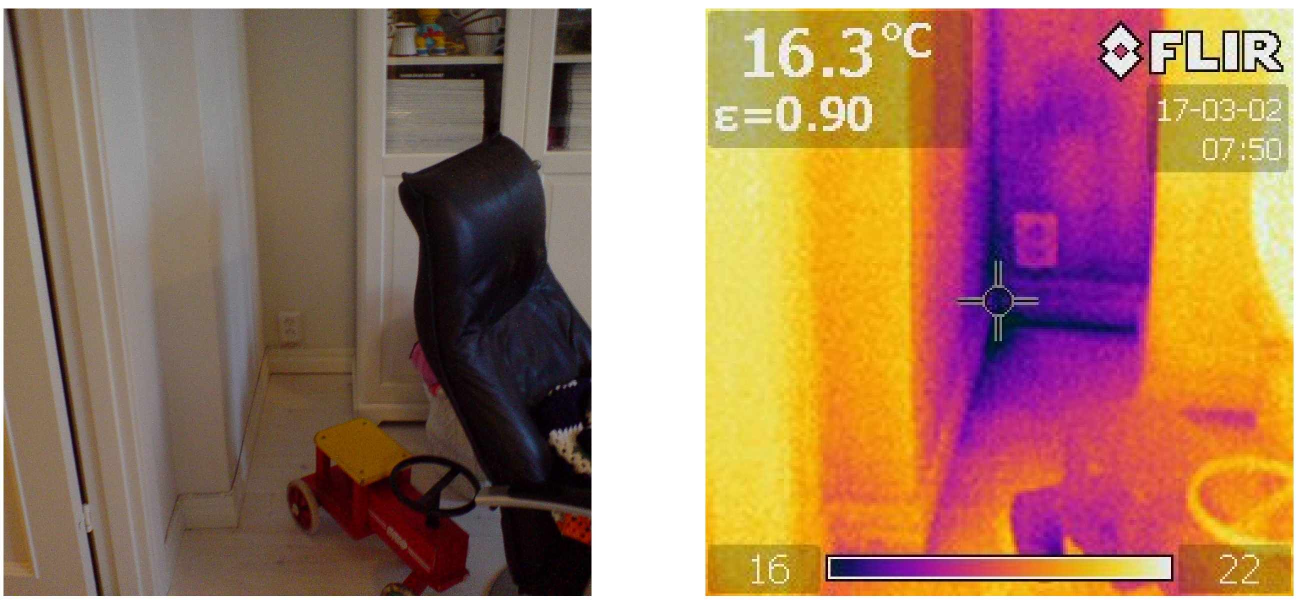


Figure 2.16: Infrared photo of outer wall to floor connection in third floor apartment. Temperature scale in Celsius.

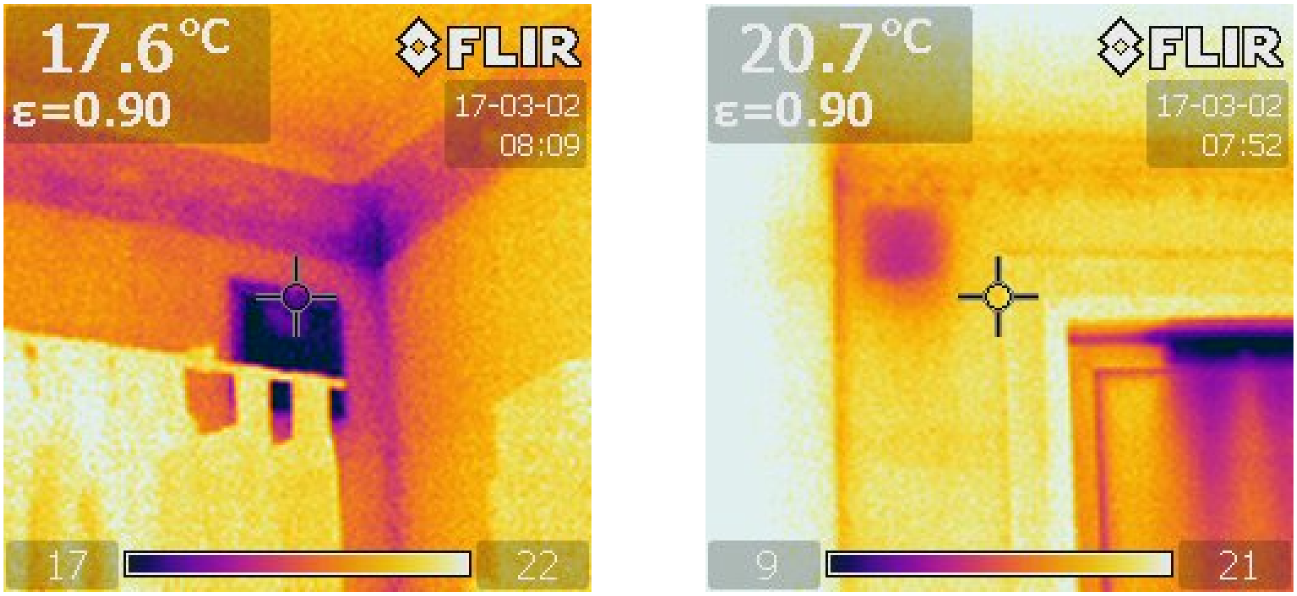


Figure 2.17: Infrared photos of covered ventilation openings in the third floor apartment. Temperature scale in Celsius.

2.5.3 Comments from tenants

The air temperatures are most often in a comfortable interval, at least not under 20 °C during winters. The radiators do not have to be on the maximum settings during winter time. The tenants sometimes leaves windows open for airing, even during winter time.

2.5.4 Restaurants

During the field visit, lunch was eaten at the larger restaurant. The front door was open the entire lunch, even though the outdoor temperature was only 10 °C. Hence, it was significantly colder in the entrance part of the restaurant than in the dining area. As seen in Figure 2.3, there is a quite open path between the entrance and the kitchen fan. This might be the reason to why a draft was experienced in the entrance area. Most of the radiators are in the dining area. There is a mix between modern and old radiators. According to the staff, the restaurant is busiest during lunch hours, where they usually have 80 to 100 guests. The number of guests during evenings varies a lot, but most often less people than during lunch.

3 Energy data

The use of district heating and electricity for each hour of 2016 was provided by Göteborg Energi. The electricity usage data is implemented in the model, see Chapter 4 for a detailed description. The district heating data mainly has two purposes. It is used for approximating the heating of tap water and for validating the model. In this chapter, the use of electricity and district heating is presented. There is also a description of how the heating of tap water is separated from the total usage of district heating.

3.1 Electricity use

Figure 3.1 shows how the daily average use electricity varied 2016. The buildings electricity use includes operating electricity, household electricity and electricity used by the restaurant. In total, the building used 140 000 kW h. The two dips in Figure 3.1 corresponds to the Swedish day of celebration "Midsummer" and Christmas holidays, when people probably go elsewhere to celebrate. It becomes evident that the use of electricity is slightly higher during winter than summer.

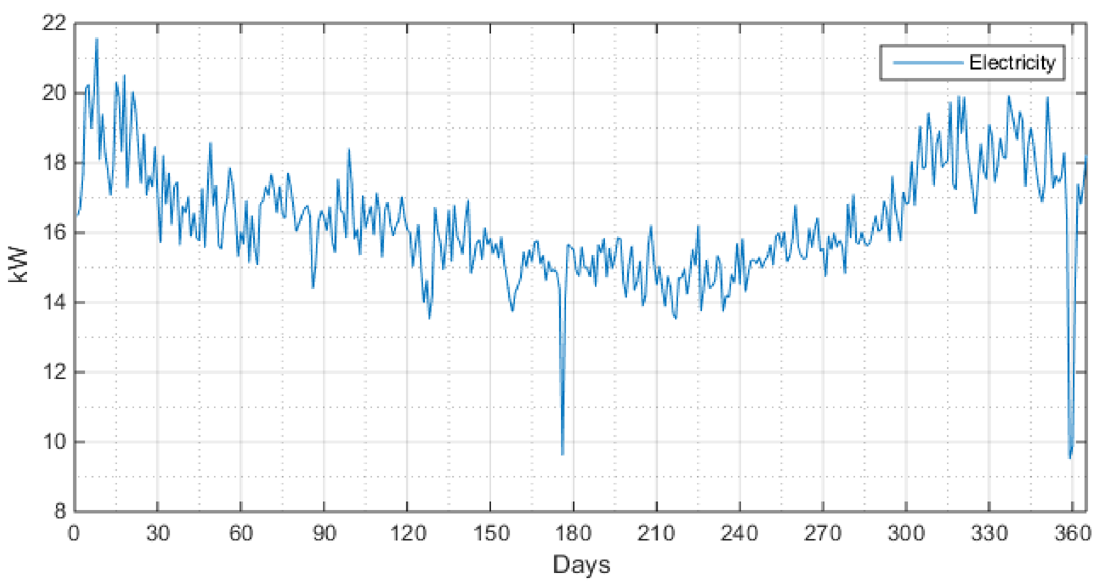


Figure 3.1: Daily average electricity use over the year 2016.

Figure 3.2 shows the average electricity use for all days 2016. The peak during mid day bear witness that the building is used for other purposes than only apartments as most people are at work during mid day.

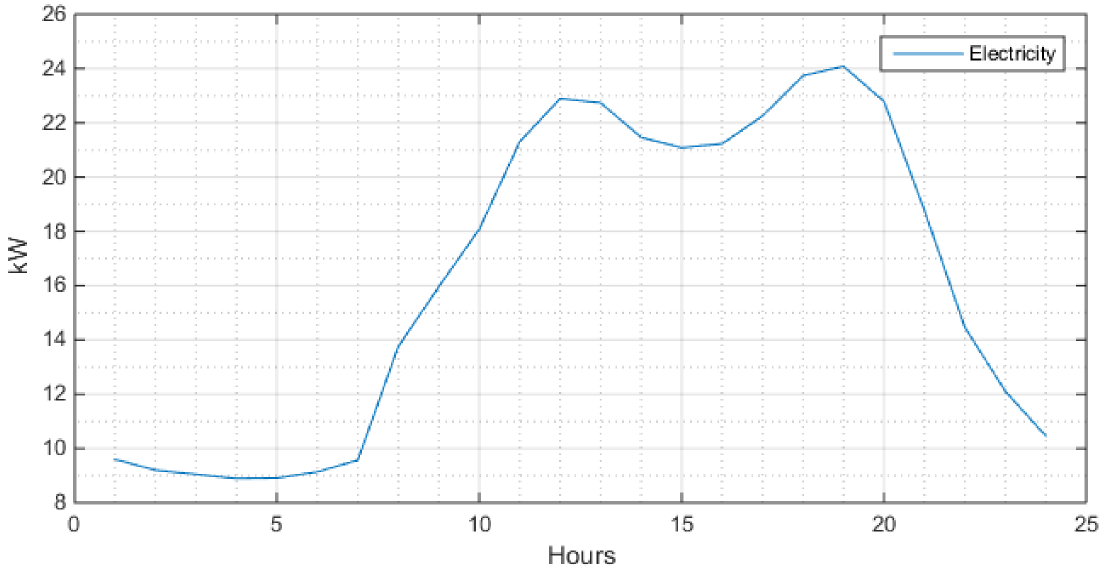


Figure 3.2: The electricity use for the average day 2016.

3.2 Use of district heating

District heating is used for heating tap water and heating the building. The total use of district heating 2016 was 250 000 kW h. The use of district heating varies over the different seasons. The daily average use of district heating is shown in Figure 3.3, where both heating of tap water and heating of the building is included.

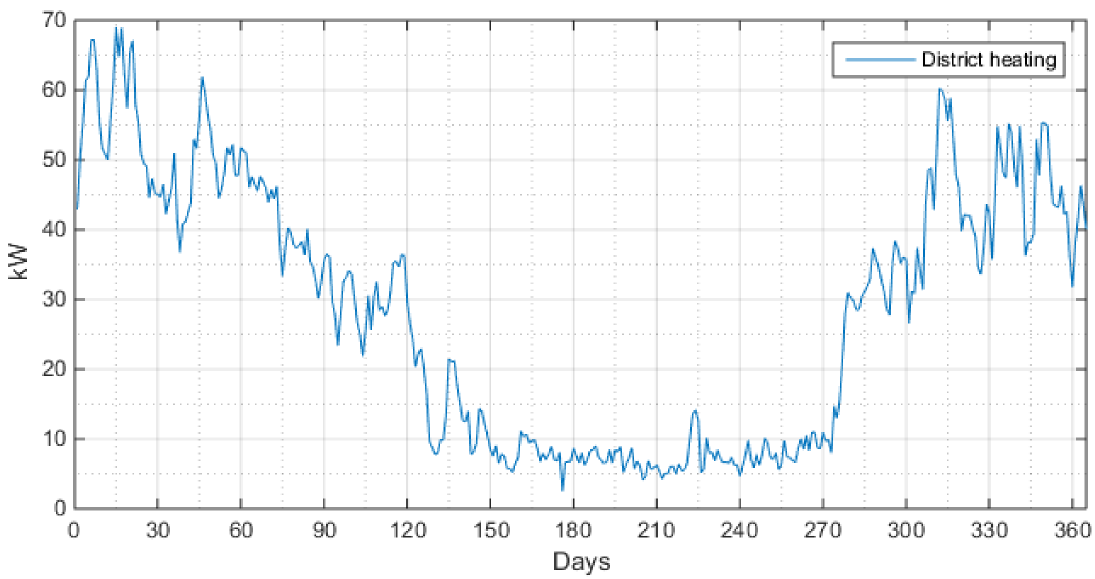


Figure 3.3: District heating use for 2016, using daily mean values.

3.2.1 Separating heating of tap water from total use of district heating

In this section, the total use of district heating is divided into heating of tap water and heating of building (through radiators). In a later stage, the heating of the building is used for validating the model while the heating of tap water is added as an internal gain.

As seen in Figure 3.3, the use of district heating is fairly constant during the summer period compared to the rest of the year. This is due to that the district heating used during the summer months is almost only for heating of tap water. This is proved in Figure 3.4 which shows a comparison of temperature and use of district heating during 15 days in June. It becomes evident that the use of district heating peaks during the day when temperatures are warm and almost hits zero at night when temperatures are low. Figure 3.4 also provides information of how the usage of tap water varies over the day. They day were almost no district heating is used again corresponds to the Swedish celebration "Midsummer".

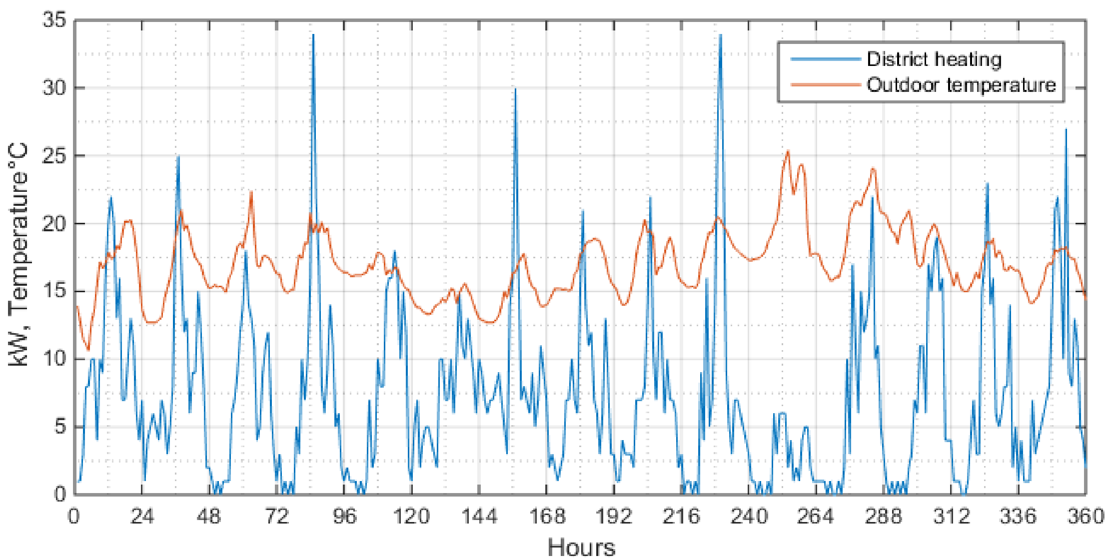


Figure 3.4: Use of district heating for 15 days in June compared to outdoor temperature (2016).

The building's heating system is however not completely shut off during summers. This is shown in Figure 3.5, where a closer look is taken on the months June, July an August. It becomes evident that for daily average outdoor temperatures under 15-16 °C there is a response from the heating system. This is especially apparent at day 70 to 75.

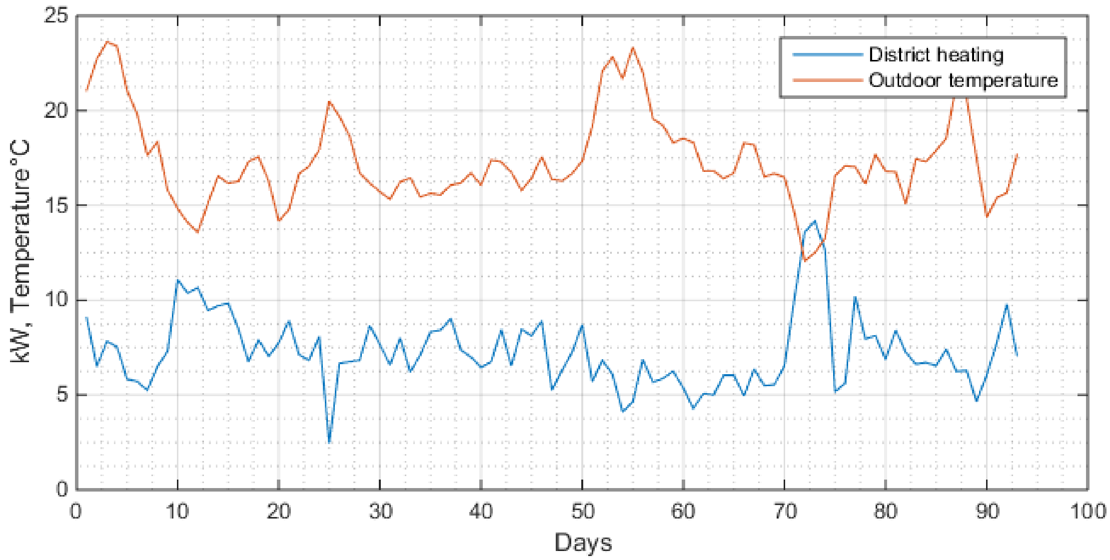


Figure 3.5: Daily average use of district heating for June, Juli and August compared to daily average outdoor temperature (2016).

When separating the heating of tap water from total usage of district heating it is of interest to include how the heating of tap water varies over the day. This was accomplished by calculating the average daily use of district heating during the months June, July and August. As there were some days where the building's heating system was on during this period, 1 kW/h was subtracted between 9:00 in the evening to 4:00 in the morning from the average day. The result can be seen in Figure 3.6, which in the model represents the heating of tap water for each day of the year. By making this assumption, a total of 61 500 kW h is approximated to be used for heating of tap water and 188 500 kW h is approximated to be used for heating the building during 2016.

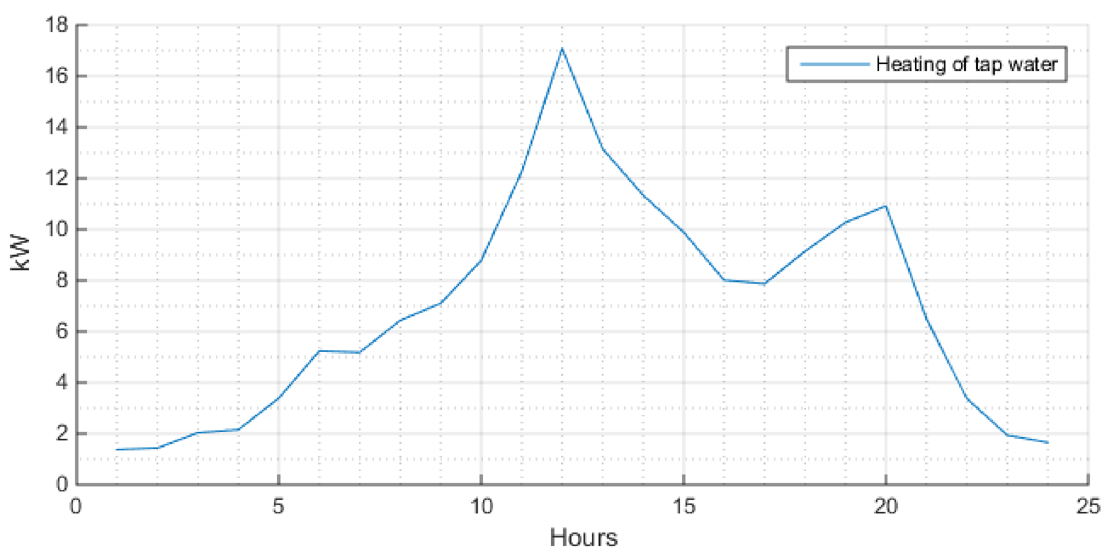


Figure 3.6: The estimated average daily heating of tap water.

4 Simulink model

In this chapter the Simulink model is described in detail. This includes the equations for which the model is based on, the assumptions made regarding input data and also how the model is verified.

The program used for calculating the energy performance of the building is called Simulink. Simulink is a Matlab plugin that allows to graphically build up equation systems. See Figure 4.1 for a visual example. In Simulink, the model is divided into five different temperature zones. The zones division is mainly based on difference in indoor temperature. The five temperature zones are:

- Attic apartments
- Second and third floor apartments
- Staircases
- Restaurants
- Storage

Each temperature zone has a unique set of input parameters dependent on internal activity, thermal envelope and ventilation. A complete list, except for the internal gains which is thoroughly described in Section 4.2, of input parameters for each temperature zone can bee found in Appendix C. Figures of the Simulink model is found in Appendix B.

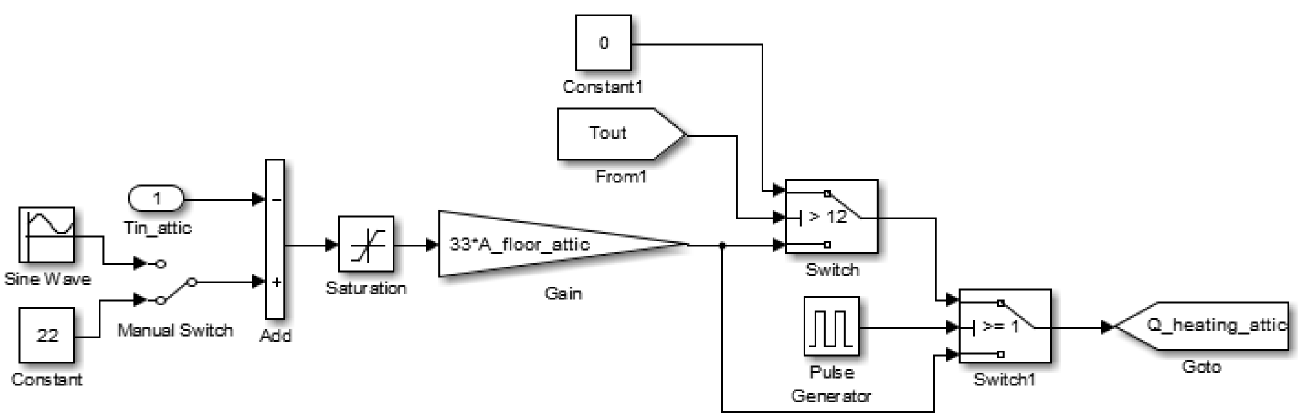


Figure 4.1: The heating system for the attic apartments modelled in Simulink.

4.1 Simulation method

The model is basically built in three steps. There are heat gains and losses that can be described by a number of equations, all found in or derived from Hagentoft (2001). There is also a heating system and there is an internal heat capacity that describes how much energy that can be stored in the structural elements of the building.

4.1.1 Gains and losses

Energy that either enters or leaves the building is referred to as gains and losses. Whether a heat flow is a loss or gain depends on the interior and exterior temperature. During heating season, the mean outdoor temperature in Sweden is lower than the indoor temperature. Hence, heat flows are referred to as as losses despite they can actually be gains for short time periods during summers.

Transmission losses

Equation (4.1) describes the energy losses through the thermal envelope by transmission. Building elements included are ground slab, walls, windows, and roof. Thermal bridges are added as a percentage, different for each building part. The sum of heat flows through all parts of the thermal envelope is equal to the total transmission loss.

$$Q_{trans}(t) = \sum_j \varphi_j \cdot U_j \cdot A_j \cdot \Delta T(t) \qquad [\mathrm{W}] \tag{4.1}$$

φ_j	is the addition for thermal bridges [-]
U_j	is the thermal transmittance [W/(m^2 K)]
A_j	is the surface area [m^2]
$\Delta T(t)$	is the current temperature difference between outdoor temperature and indoor temperature [K]

Ventilation losses

Equation (4.2) is used to calculate the ventilation losses. In the model, ventilation losses includes opening of doors and windows. The air flows for the different temperature zones varies over time, see Section 4.2.2.

$$Q_{vent} = \sum_j R_{a,j}(t) \cdot \rho_a \cdot c_{pa} \cdot \Delta T(t) \qquad [\mathrm{W}] \tag{4.2}$$

$R_{a,j}(t)$	is the airflow through the building envelope at the time t [m^3/s]
ρ_a	is the density of air [kg/m^3]
c_{pa}	is the heat capacity of air [J/(kg K)]
$\Delta T(t)$	is the current temperature difference between outdoor temperature and indoor temperature [K]

Air leakages

The leakages through the climate envelope are calculated in two steps. The air tightness of a building is often presented in the unit $\mathrm{l/(s\,m^2)}$ (envelope area) at 50 Pa pressure difference. In reality, the average pressure difference between indoor and outdoor is about 4 Pa (Wetterlund, 2017). Equation (4.3) is used to approximate the air flow corresponding to a 4 Pa difference in pressure. Equation (4.4) is used to calculate the loss due to leakages.

$$R_{a,4}(t) = R_{a,50}(t)/25 \qquad [\mathrm{m^3/(s\,m^2)}] \tag{4.3}$$

$$Q_{leakage} = R_{a,4}(t) \cdot A_{envelope} \cdot \rho_a \cdot c_{pa} \cdot \Delta T(t) \qquad [\mathrm{W}] \tag{4.4}$$

$R_{a,50}(t)$	is the airflow through the building envelope at the time t and pressure difference 50 Pa $[\mathrm{m^3/(s\,m^2)}]$
$R_{a,4}(t)$	is the airflow through the building envelope at the time t and pressure difference 4 Pa $[\mathrm{m^3/(s\,m^2)}]$
$A_{envelope}$	is the area of the envelope $[\mathrm{m^2}]$
ρ_a	is the density of air $[\mathrm{kg/m^3}]$
c_{pa}	is the heat capacity of air $[\mathrm{J/(kg\,K)}]$
$\Delta T(t)$	is the current temperature difference between outdoor temperature and indoor temperature [K]

Solar radiation gains

Solar radiation that shines through windows contributes to heating the building. Solar radiation from nine angles are included: north, north-east, east, south-east, south, south-west, west, north west and horizontal. The radiation is also divided into diffuse and direct and for the later the angle of incidence is included. The angel of incidence affects the windows transmittance of direct solar radiation. Equation (4.5) describes the total energy gains from solar radiation after all coefficients have been added.

$$Q_{solar} = \sum_j A_{w,j} \cdot W_{s,j} \cdot (I_{D,j} \cdot \tau_D(\phi) + I_{d,j} \cdot \tau_{d,j}) \qquad [\mathrm{W}] \tag{4.5}$$

$A_{w,j}$	is the window area $[\mathrm{m^2}]$
$W_{s,j}$	is the shading coefficient [-]
$I_{D,j}$	is the direct solar radiation $[\mathrm{W/m^2}]$
$\tau_{D,j}(\phi)$	is the window's transmittance of direct solar radiation dependent on the angle of incidence [-]
$I_{d,j}$	is the diffuse solar radiation $[\mathrm{W/m^2}]$
$\tau_{d,j}$	is the window's transmittance of diffuse solar radiation [-]

Internal heat gains

Equation (4.6) describes the gains from anything in the house producing heat. For a description of how each internal gain is treated, see 5.2.3 (Internal gains).

$$Q_{int} = Q_{people} + Q_{el} + Q_{tw} + Q_{gas} \qquad [\text{W}] \tag{4.6}$$

Q_{people}	is the heat generated by people in the building [W]
Q_{el}	is the heat generated by household electricity use in the building [W]
Q_{tw}	is the heat generated by hot tap water use. [W]
Q_{gas}	is the heat generated by a gas-stove in the restaurant [W]

4.1.2 Internal heat capacity

The internal heat capacity of a building affects how the indoor climate reacts to a change in outdoor climate. A building with high internal heat capacity can buffer more heat in its construction elements. One usually talk about thermally light and heavy buildings. A light building have a low internal heat capacity compared to its thermal conductance while its the other way around for a heavy building. One way to put a number to this "inertia" of buildings is to calculate its time constant, t_c. Buildings with a high time constant can keep a steadier indoor temperature. This can save energy for the building by using buffered heat instead of the heating system to compensate for a drop in outdoor temperature during a shorter time period.

$$t_c = C/K_{tot} \qquad [\text{s}] \tag{4.7}$$

$$C = \sum_j d_j \cdot \rho_j \cdot A_j \cdot c_{p,j} \qquad [\text{J/K}] \tag{4.8}$$

K_{tot}	is the total thermal conductance of the building [W/K]
d_j	is the thickness of each layer in contact with the indoor air [m]
ρ_j	is the density of each layer in contact with the indoor air [kg/m^3]
A_j	is the area of each layer in contact with the indoor air [m^2]
$c_{p,j}$	is the specific heat capacity of each layer in contact with the indoor air [J/(kg K)]

4.1.3 Heating system

The heating system for each temperature zone can be described by Equations (4.9) to (4.11). In words, the effect of the heating system is increasing linearly with the difference in indoor temperature and set point indoor temperature. When the difference is 2 °C or more, the heating system is running on its maximum effect. If the indoor temperature is over the set point temperature, the heating system shuts off.

$$Q_{heating} = (T_{target} - T_{in}) \cdot P/2 \quad \text{for} \quad 0 > T_{target} - T_{in} \leq 2 \tag{4.9}$$

$$Q_{heating} = P \quad \text{for} \quad T_{target} - T_{in} > 2 \tag{4.10}$$

$$Q_{heating} = 0 \quad \text{for} \quad T_{target} - T_{in} \leq 0 \tag{4.11}$$

T_{target}	is the set point indoor temperature [K]
T_{in}	is the indoor temperature [K]
P	is the thermal conductance of the heating system [W/K]

There is however one exception. Between the 4th of May to the 26th of September the heating system shuts off at outdoor temperatures over 12 °C in all of the temperature zones. This time interval and temperature is found based on the measured energy use in order to improve correlation between the Simulink model and measured data of district heating.

4.1.4 Energy balance equation

The model assumes that the indoor air temperature and the temperature of all internal layers are the same. The change of indoor air temperature over time is described in Equation (4.12).

$$C * \frac{dT_{in}(t)}{dt} = Q_{trans}(t) + Q_{vent,leakage}(t) + Q_{solar}(t) + Q_{int}(t) + Q_{heating}(t) \tag{4.12}$$

Equation (4.12) is numerically integrated in Simulink according to Equation (4.13)

$$\int_{t}^{t+\Delta t} \frac{dT_{in}(t)}{dt} = T_{in}(t + \Delta t) - T_{in}(t) \tag{4.13}$$

Thus Equation (4.14) describes the final energy balance for calculating the indoor temperature for the next time step.

$$T_{in}(t + \Delta t) = T_{in}(t) + \frac{Q_{trans}(t) + Q_{vent,leakage}(t) + Q_{solar}(t) + Q_{int}(t) + Q_{heating}(t)}{C} \tag{4.14}$$

A fixed time step of $\Delta t = 30$ min is used for simulations. The weather data only gives hourly values. For the points in between data, Simulink uses interpolation.

4.2 Assumptions made in model

The input parameters have been collected from drawings, literature, interviews, field visits and in some cases qualitative guessing. In this chapter the assumptions and origins regarding the choice of input parameters will be explained.

4.2.1 Transmission losses

For an old house thermal bridges are common and need to be taken into consideration when estimating transmission losses. Usually 15-20 % is added to U-values of walls and roofs etc. in order to compensate for thermal bridges (Wetterlund, 2017). In the model this, addition varies for different parts of the thermal envelope (See Appendix A). Homogeneous parts have been approximated to be in the lower range, while parts with a lot of irregularities have been placed in the higher range. Findings from the studied building have also been taken into consideration.

4.2.2 Ventilation

The minimum demand on air flow for residential buildings is $0.35\,\mathrm{l/(s\,m^2)}$ (Levin, 2012a). However, according to Mattsson, Carlsson, Te, and Pluntke (2010), the average air flow for multi-family buildings is a little bit higher, $0.37\,\mathrm{l/(s\,m^2)}$. Further it is stated that multi-family buildings with exhaust ventilation have higher air flow than the same type of buildings with other ventilation systems. The ventilation rate for the building is therefore estimated to be higher than average, i.e. $0.40\,\mathrm{l/(s\,m^2)}$.

Apartments

For apartments, natural ventilation through windows, i.e. opening them for supply of fresh air, has also been taken into account. There are some different approaches to handle natural ventilation when modelling according to Levin (2012a). The simple way is to add $4\,\mathrm{kW\,h/(m^2\,year)}$ to the losses. The disadvantage with using this method is that the opening of windows will not influence the indoor temperature in the model. Instead an airflow of $42\,\mathrm{l/(s\,window)}$ have been used when windows are opened. The set point for natural ventilation have been chosen to 24 °C. In the model, it is approximated that the occupants open one window in each apartment when the indoor temperature reaches the set point temperature. However, the indoor temperature for when the window should close is decided so that the total losses become around $4\,\mathrm{kW\,h/(m^2\,year)}$. Forcing of kitchen fans are also included in the model by adding $25\,\mathrm{l/s}$ for half of the apartments between 17:00 to 19:00 each day. According to Levin (2012a) forcing of kitchen fans should be inserted between 17:00 and 17:30 and the air flow for a regular kitchen fan is about $100\,\mathrm{l/s}$ (kitchen systems, 2016). However, that all apartments in the building should force their kitchen fans for half an hour at the same time each day is unreasonable and so were the results. Hence the decreased air flow and longer time interval.

Restaurants

For lunch restaurants the suggested input flow for ventilation according to Levin, 2012b is $8\,\mathrm{l/(s\,m^2)}$. This has been used during the lunch hours. According to the staff in the larger restaurant, lunch hours are busier than evenings and the time in between is pretty calm. One can also see in Figure 4.3 (left) how the electricity use drops after lunch time. This might partly be due to less use of kitchen appliances, for example kitchen fans. Table 4.1 shows the resulting ventilation scheme for the restaurants.

Table 4.1: The approximated air flow in the restaurants for each hour of the day

Time of day	$\mathrm{l/(s\,m^2)}$	$\mathrm{m^3/s}$
00:00 - 09:00	0.35	0.09
09:00 - 11:00	4.00	0.97
11:00 - 14:00	8.00	1.94
14:00 - 17:00	4.00	0.97
17:00 - 20:00	5.00	1.22
20:00 - 21:00	4.00	0.97
21:00 - 22:00	2.50	0.61
22:00 - 24:00	0.35	0.09

4.2.3 Leakages

Leakages are measured at a pressure difference of 50 Pa. The highest allowed value according to BBR is $0.6\,\mathrm{l/(s\,m^2)}$ (Boverket, 2011). For old buildings the leakages are often higher. The leakages for the studied building is therefore estimated to $0.6\,\mathrm{l/(s\,m^2)}$ at a pressure difference of 50 Pa. In reality the average pressure difference is closer to 4 Pa (Wetterlund, 2017). This corresponds to about 4 % of the air flow at 50 Pa.

4.2.4 Internal gains

The internal gains from people and electricity are limited to apartments and restaurants. In the storage area only gains from circulation of tap water is considered.

Energy from people

The energy from people living in apartments is treated as suggested in the report by Levin (2012a). Each person produces 80 W and is home 14 hours per day. In the model people are assumed to be out of home between 7:30 and 17:30. According to Eniro Sverige (2016) there are 35 people living in the building. As follows, people living in the apartments produces 2800 W between 17:30 in the afternoon until 7:30 in the morning. The gains from people are evenly spread out per square meter apartment area.

Calculations of internal gains from people in restaurants during lunch hours are handled as proposed by Clarholm (2014). In the thesis, a difference is made between the staff and guests of the restaurants. The energy produced by the staff is $180\,\mathrm{W/person}$ and there are $0.11\,\mathrm{person/m^2}$ kitchen area. The energy produced by guests is $110\,\mathrm{W/person}$ and there are $0.2\,\mathrm{person/m^2}$ dining area. The rest of the day is approximated based on a field visit (April, 2017) and interview at the larger restaurant, see Table 4.2.

Table 4.2: Number of people and their contribution of heating the restaurants for each hour of the day.

Time of day	people/h	Gains (W)
00:00 - 09:00	0	0
09:00 - 11:00	5	677
11:00 - 14:00	45	5077
14:00 - 17:00	10	1227
17:00 - 21:00	20	2327
21:00 - 22:00	10	1227
22:00 - 24:00	0	0

Heating gains from electricity

For 2016 the building's total use of electricity was 143 MW h.This includes facility electricity (exhaust ventilation, pumps, lighting in common areas and floor heating in the attic apartments), household electricity and electricity used by the restaurants.

As there are as much as 21 apartments in the building, it can be assumed that standardised values for apartments electricity use will provide a reasonably good estimation of the total use of electricity for the apartments. Further the facility electricity can also be estimated based on the design of the heating and ventilation system. The electricity used in the restaurants is most difficult to determine. This is estimated from the energy bill by subtracting facility electricity and household electricity.

The use of household electricity for residential buildings are 2000 kW h/(year apartment) and 800 kW h/(year person) (Levin, 2012a). With 21 apartments and 35 residents, the total use of household electricity is 70 MW h/year. However, the apartments in the building are smaller than average which could be an indicator of that this value is overestimated (Wetterlund, 2017). Wetterlund instead suggest to use a value of 30 kW h/(m^2 year) which gives a total value of 48 MW h/year. In simulations 59 MW h/year is chosen as a target value as it is in the middle of the two values.

The equipment responsible for use of the facility electricity are circulation pumps, exhaust fans, floor heating and lighting in common areas. The electricity used by the circulation pumps can be estimated to be equal to 5 % of the total energy applied through district heating (Wetterlund, 2017). This estimation gives an electricity use for the circulation pumps of 12 000 kW h/year. The exhaust fans have been given a specific fan power of 1.5 kW h/(m^3 s). For new fans, the specific fan power is usually between 0.5–1 kW h/(m^3 s) (Ahlsell, 2010) but as the exhaust fans for storey two and three were installed during the seventies, a higher value has been estimated. The total exhaust flow out of the building is 0.66 m^3/s. Hence the exhaust fans use 8650 kW h/year. A notation should be made that the increased exhaust flow due to kitchens fans is not included in this number. This is due to that kitchen fans are categorized as household electricity (Levin, 2012a). The floor heating in attic apartments uses 1000 kW h/(year apartment) (Levin, 2012a). Since there are 5 attic apartments the total energy used by floor heating becomes 5000 kW h/year. The energy use of lighting in the staircases is neglected. The total facility electricity for the property is then 25 650 kW h/year. For our building this is equal to 16 kW h/(m^2 year) (tempered area) which is close to 15 kW h/(m^2 year) (tempered area) which is the recommended value (Levin, 2012a). As the exhaust fans are placed on the roof, their use of electricity do not contribute to heating the building. The circulation pump's contribution to heating the building is also neglected (Wetterlund, 2017). All of the electricity used for floor heating is however assumed to heat up the attic. An overview of the facility electricity is given in Table 4.3 and the final distribution of total electricity use is shown in Table 4.4

Table 4.3: Overview of the facility electricity.

Function	Electricity use (kW h/year)
Circulation pumps	12000
Exhaust fans	8650
Floor heating	5000
Lighting	-
Total	25650

Table 4.4: Overview of the building's total electricity use.

Location	Electricity use (kW h/year)
Apartments	59000
Facility electricity	25650
Restaurants	58350

In the model, these numbers are used as guidelines for how to divide the daily use of electricity between the apartments and restaurants. The use of facility electricity is assumed to be constant over the whole year. The electricity used in the apartments and the restaurants varies over the day. The average daily measured electricity use for 2016 without the facility electricity looks as follows:

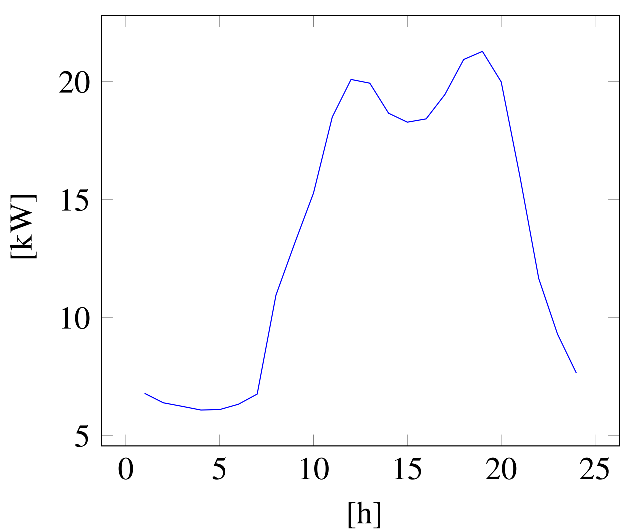
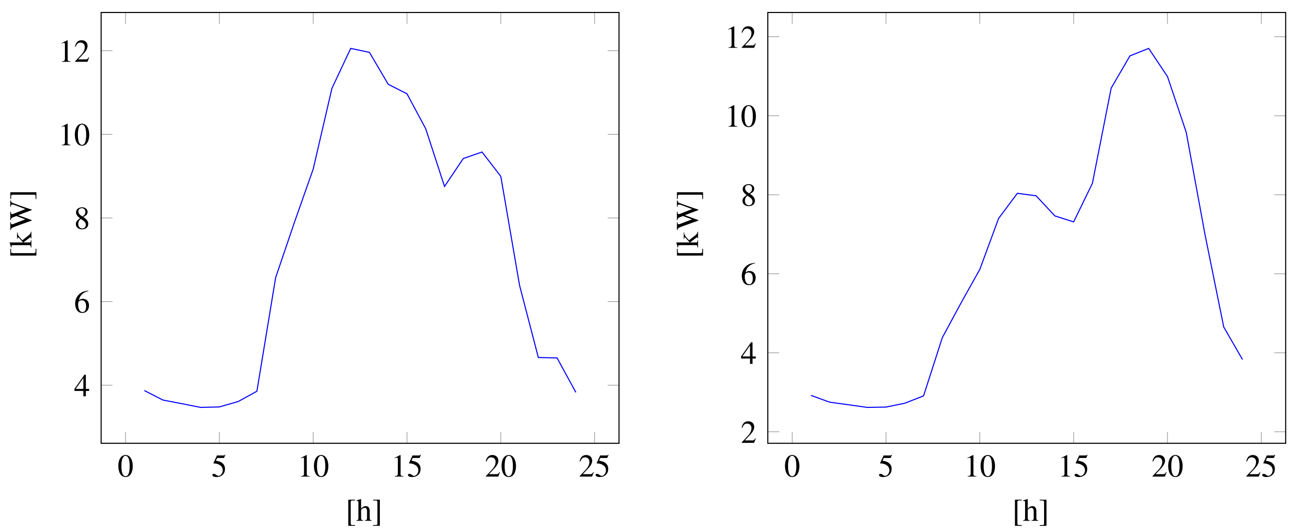


Figure 4.2: averaged daily measured electricity use for restaurants and apartments.

The daily electricity use of restaurants and apartments needs to be separated in a way that seems reasonable and matches the previous calculated results of yearly electricity use. By analysing Figure 4.2, one can notice that the electricity use during the night is fairly constant. The main electricity consumers in apartments during nights are refrigerators, freezers and equipment on stand-by. According to Wetterlund (2017) this is around 2 W/m^2, or 2.5 kW in total for all apartments. By studying the amount of electricity used by different household items in Levin (2012a) and Göransson (2006) it becomes evident that the estimation made by Wetterlund seems very reasonable. The remaining electricity, approximately 3.5 kW, is assumed to be used by the restaurants.

In an short interview with the larger restaurant it was stated that it is most busy during lunch time, with between 80–100 guests during the time interval 11:00 to 14:00. This probably correlates with the peak seen in Figure 4.2 between these hours. During the evenings, the number of guests varied but they where generally fewer than during lunch. For the apartments on the other hand, the electricity use is highest on the evenings when people are preparing dinner, watching television or computers and having lights switched on. Based on these assumptions, the following division was estimated.



(a) Restaurants.

(b) Apartments.

Figure 4.3: Mean daily electricity use for the restaurants (left) and apartments (right).

By dividing the electricity in this way, around 62 500 kW h/year is used by the restaurants and 55 100 kW h/year is used by the apartments. This correlates reasonably well with the previously calculated yearly values. For both the restaurants and apartments, 70 % of the used electricity contributes to heating the building (Levin, 2012a).

Solar Radiation Through Windows

Solar radiation through windows contributes to heating up the building. In the model around 75 % (depending on type of window) of the energy is assumed to be transmitted through the glass (Olsson-Jonsson & Ekstrand-Tobin, 2011). A further 50 % of the radiation is assumed to be lost through shading

(Levin, 2012a). For the storage part of the building, 80 % shading is assumed, this is based on site observations.

Other gains

During the visit at the larger restaurant it was noticed that a gas-stove is used. Hence some extra gains have been added. According to several different gas-stove producers, one burner can produce as much as 4000 W. However, as the burners are directly under the kitchen fan, heating gains from the stove are assumed to be considerably less. Table 4.5 shows how heating gains from the stove have been added to the restaurant.

Table 4.5: The gas-stoves contribution of heating the restaurants

Time of day	Gains (W)
11:00 - 14:00	1400
14:00 - 17:00	200
17:00 - 21:00	700

The hot tap water use also creates internal gains. This is mainly due to heat losses through the water circulation pipes (Wetterlund, 2017). According to Levin (2012a), 20 % of the energy needed to heat tap water contributes to heating the building. In the model, the heating from tap water use is assumed to be constant throughout the day.

4.2.5 Internal heat capacity

As seen in Equation (4.8) heavy and thick materials often result in a larger heat capacity. As the studied building is mainly constructed out of wood, which is a light material, its heat capacity is relatively low. Further more, the thermal conductance is quite large as the building is ventilated with outdoor air and has a relatively thin layer of insulation. Only the material layer in direct contact with the indoor air is assumed to contribute to the buildings internal heat capacity. The indoor surface area for each material is estimated via CAD-drawings. The information of indoor surface materials and their thicknesses have been gathered from drawings and observations. The total heat capacity for the building is calculated according to Equation (4.8). The result is a heat capacity of 2×10^8 W s/K and a time constant of 20 h during the night. During the day the time constant is lower due to increased ventilation losses in the restaurants.

4.2.6 Heating system

The total power that the building's heating system is able to produce has been derived empirically from the data of district heating use during 2016. The maximum effect produced during 2016, excluding heating of tap water, was 60 W/m^2 heated area. This was used as a guideline when deciding the maximum power of the building's heating system. It was assumed that the actual maximum effect of the heating system could be designed slightly higher as all radiators not necessarily where set on max at the same time.

The power has been distributed between all temperature zones, see Table 4.6. The distribution is based on the number of radiators spotted during field visits.

Table 4.6: The power and target temperature for each temperature zone

Temperature zone	Power (W/m^2)	Target temperature (°C)
Attic	66	22
Floor 2 and 3	66	22
Restaurants	132	20
Staircases	48	18
Storage	66	12

As seen in Table 4.6 the target temperature also differs for the different temperature zones. According to Levin (2012a) an indoor temperature of 21 °C should be approximated for multi-family buildings. The target indoor temperature for the apartment area was however set slightly higher based on field visits. The same indoor temperature is recommended for office buildings (Levin, 2012b) but there are no specific recommendations for restaurants. The target indoor temperature for the restaurants is instead based on the field visit. Regarding the staircases and storage no recommendations were found.

4.2.7 Weather data

The weather data used in the model is measured in Gothenburg during 2016. The data that is used consists of hourly values of outdoor temperature, direct and diffuse solar radiation (both horizontally and for each direction of the compass) and cloudiness. The temperature and cloudiness can be downloaded from SMHI(2017) (Sveriges meteorologiska och hydrologiska institut) but he solar radiation is only provided as the global radiation. A MATLAB script was used in order to get the solar radiation from all angles and separate direct and diffuse radiation. The MATLAB script is working according to the method described in Nik (2010).

4.3 Verifying the model

Mainly three methods have been used to verify the model. First of all, the indoor temperature of each temperature zone has been analysed. Second, the actual annual use of district heating for 2016 has been compared to the annual use according to the model. Third, the hourly variation over 24 hours of district heating have been compared.

4.3.1 Indoor temperatures

The indoor temperature is highly influenced by the outdoor temperature. Figure 4.4 shows the variation in outdoor temperature during 2016 in Gothenburg. One can see that it peaks at 30 °C during the summer and −15 °C during winter.

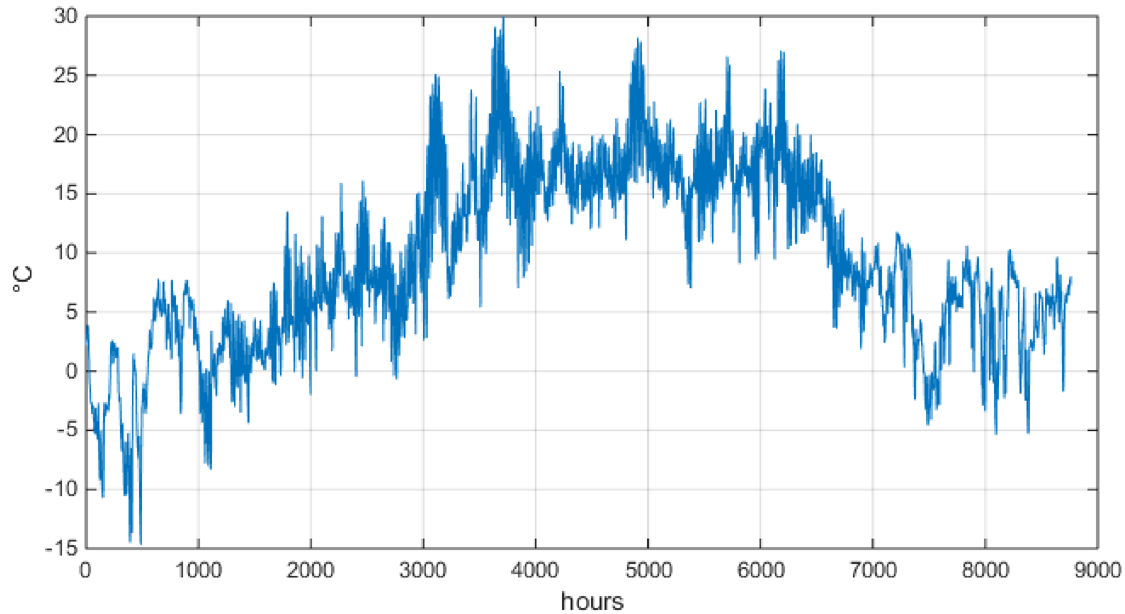


Figure 4.4: Measured outdoor temperature variation in Gothenburg during 2016.

The indoor temperature in residential buildings should not be below 20 °C (Socialstyrelsen, 2006). Figure 4.5 shows the indoor temperature in the attic apartments and storey two and three.

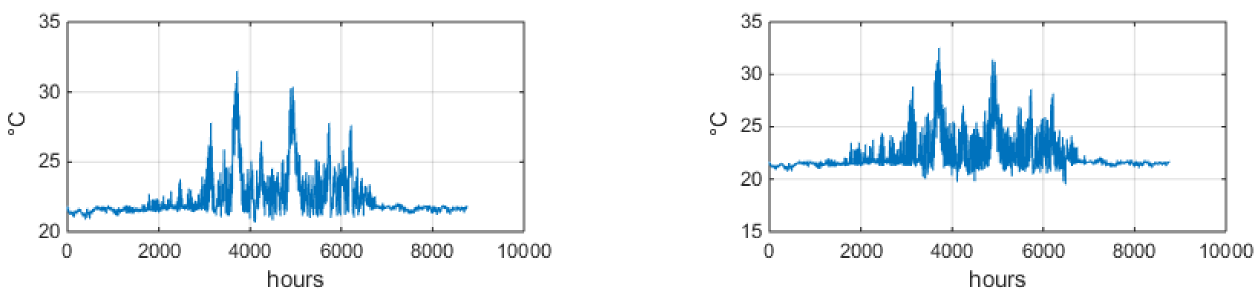


Figure 4.5: Calculated indoor temperature variation during 2016 for the attic apartments (left) and storey 2 and 3 (right).

The indoor temperature becomes quite high during the summer, but never more than a few degrees over the outdoor temperature. As the only way of cooling the apartments is by natural ventilation, this is reasonable. The temperature rarely falls under 20 °C, which is in line with what was stated during interviews with the residents.

The calculated indoor temperature in the storage area is in a lower span, see Figure 4.6. It is assumed that the owner of the storage has interest in keeping the temperatures as low as possible, due to financial reasons. Figure 4.7 shows the calculated indoor temperature in the restaurants.

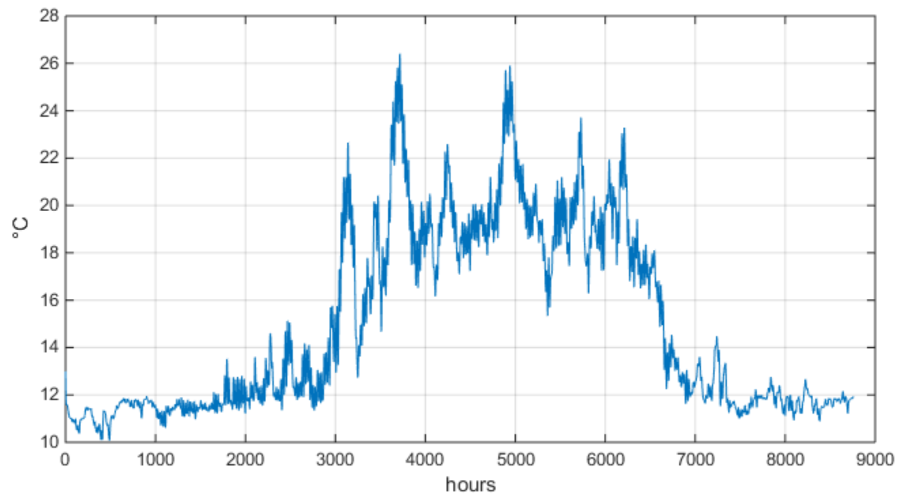


Figure 4.6: Calculated indoor temperature variation during 2016 for the storage area.

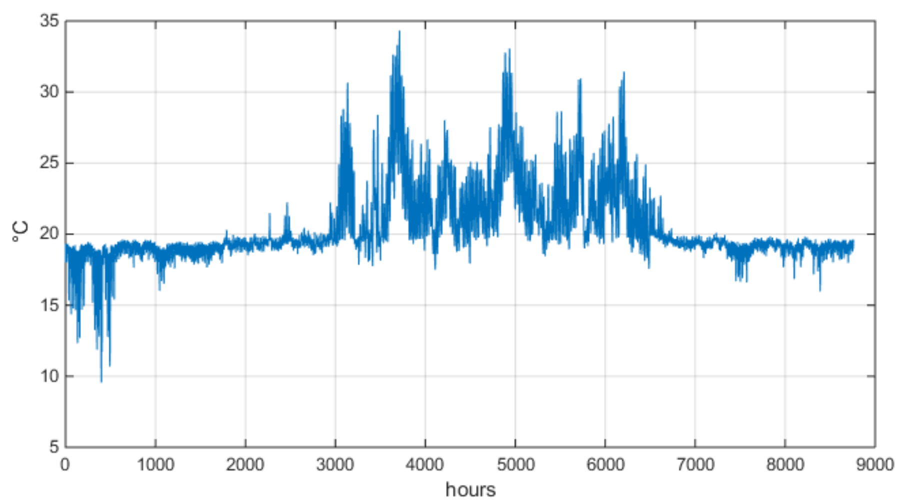


Figure 4.7: Calculated indoor temperature variation during 2016 for the restaurants.

Most of the year, the indoor temperatures in the restaurants are quite stable around 18 °C. In the model, the entrance, kitchen and dining area are assumed to have the same indoor temperature. In reality, the air could be colder in the kitchen and entrance than in the dining area. It all depends very much on where the air inlets and radiators are situated. For example in the larger restaurant most of the radiators are situated in the dining area. It should also be remembered that the model assumes all indoor surfaces to have the same temperature as the indoor air. The increase in operative temperature due to radiation from all hot surfaces existing in a kitchen is not included in the model. In the beginning of the year, however, indoor temperatures are going down to unreasonably low temperatures. Figure 4.8 shows the week with lowest indoor temperature in the restaurants.

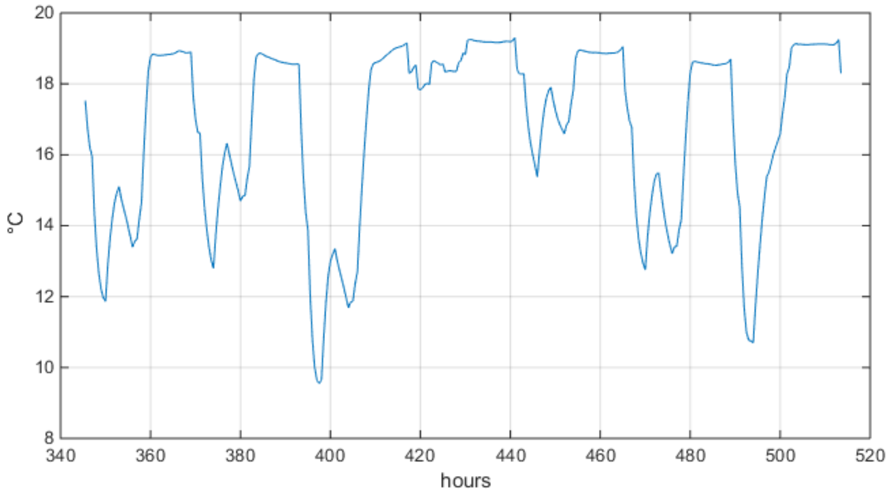


Figure 4.8: Week with lowest indoor temperature for restaurants.

It can be seen that there are two drops in temperature each day. They correlate well with the increased ventilation in the restaurants that is modelled during lunch and dinner hours. This is due that the restaurants are using outdoor tempered air for ventilation. The dips in indoor temperature bear witness that either the ventilation is over estimated or the model's heating system underestimated.
In the model, the ventilation rate is the same, independent of outdoor temperature. One could imagine that the restaurants keeps most of the openings closed during the coldest winter days. This would most likely decrease air exchanges due to increased resistance in inlet air flow.

4.3.2 Annual use of district heating

Figure 4.9 shows the annual use of district heating according to the Simulink model compared to the building's measured use of district heating during 2016. The difference in annual energy use is less than 0.5 %. However, at most of the times during the year, the difference is larger.

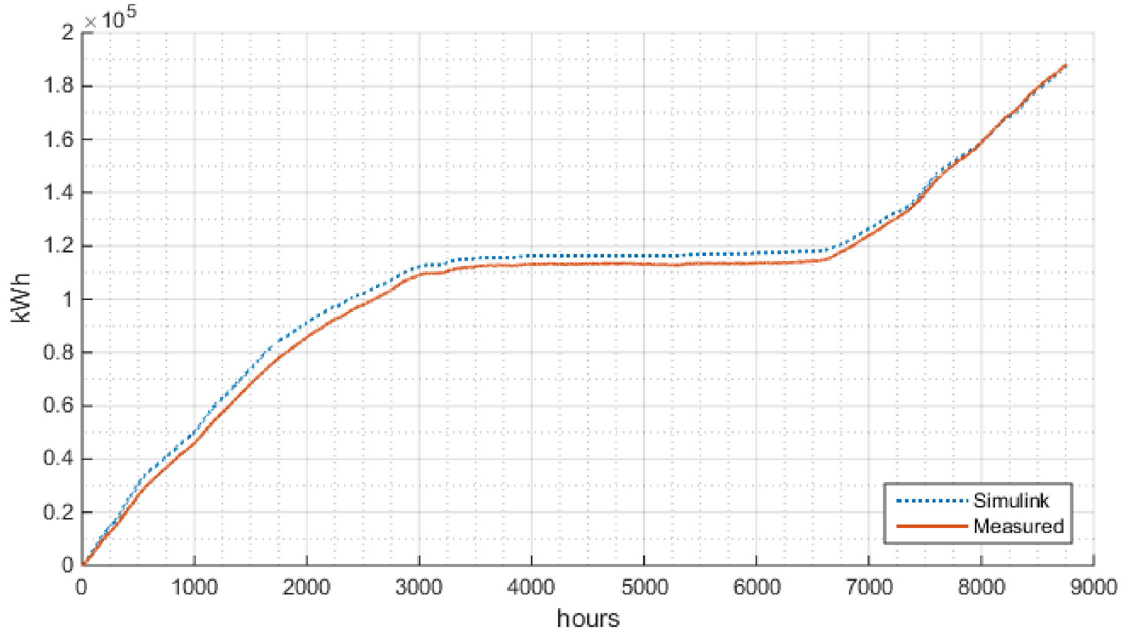


Figure 4.9: The dotted line displays the results from Simulink while the filled line is the measured energy use for 2016.

If comparing Figure 4.9 with the outdoor temperature (Figure 4.4) some trends can be spotted. When mean outdoor temperatures are around −5 °C or colder the model uses more district heating than in reality. This is in line with the previous analysis that the restaurant ventilation might be overestimated during the coldest days. During mean temperatures from 0–10 °C the model either uses less or equally much district heating compared to reality. During summer, the heating system is assumed to be more or less shut off (Section 4.1.3) so here the simulations and measured values correlate nicely.

Another parameter that affects the use of district heating is wind speed. Increased wind speed causes greater leakages (Sandberg, Sikander, Wahlgren, & Larsson, 2007). In Figure 4.10, wind speed is plotted against outdoor temperature. The wind speed is gathered from SMHI(2017). For some unknown reason, all wind speeds below 0.5 m/s is denoted as zero.

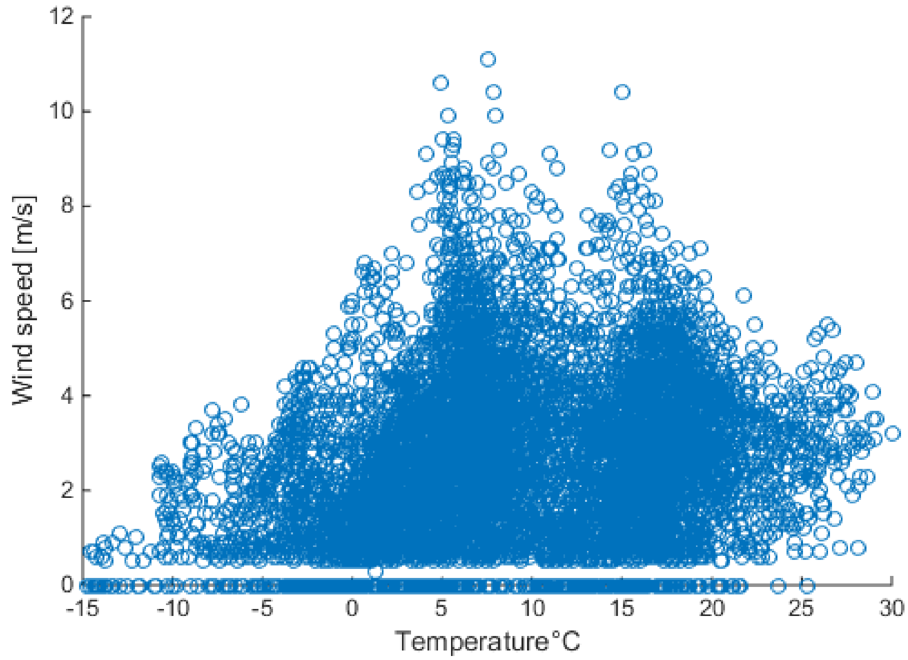


Figure 4.10: Wind speed plotted against outdoor temperature for Gothenburg 2016.

The wind is most prominent at temperatures over 3 °C and the highest speeds occurs around 6 °C. As the leakages in the model are not wind dependent, this could be one of the reasons for why the model uses less district heat during these temperature intervals compared to measured values. The exterior surface resistance is also decreasing with increased wind speeds. This have an influence on poorly insulated walls and poor windows. The model uses the exterior surface heat transfer coefficient of 0.04 $W/(m^2 K)$, irrespective of wind speed.

4.3.3 Daily use of district heating

A comparison of hourly use of district heating between model and measured values has been made. By taking the mean value for each hour of the day during 2016 the average day has been produced. Figure 4.11 shows the average day from measured values compared to the model. One should however remember that the estimated heating of tap water have been subtracted from the measured values. This definitely have an influence on the average hourly variations in use of district heating that is displayed in the figure.

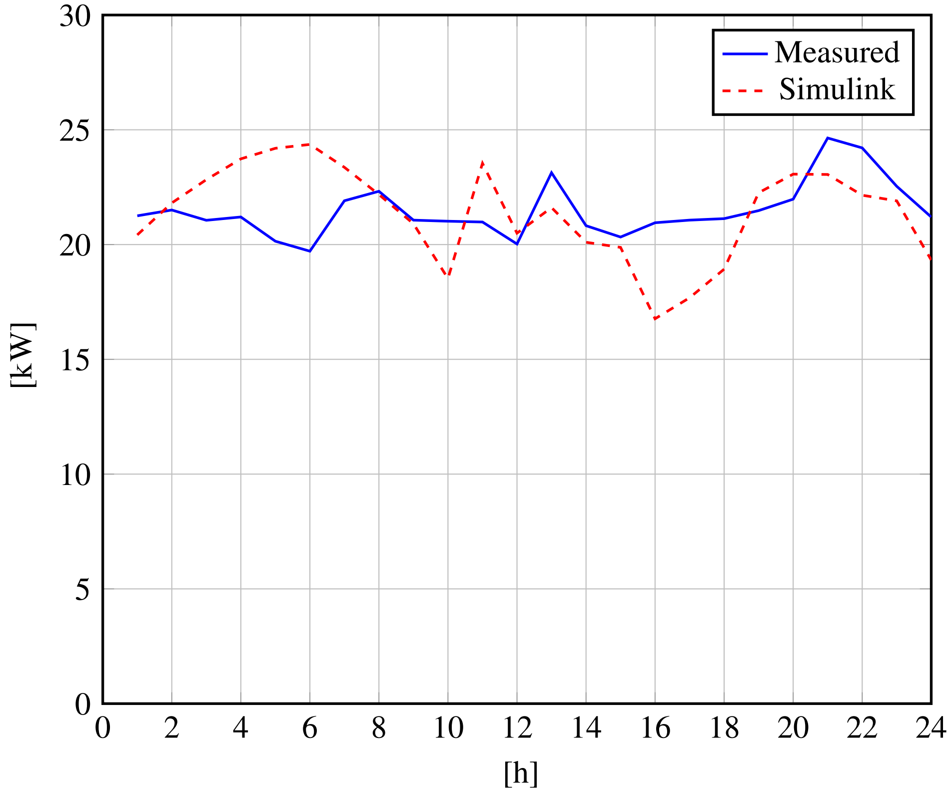


Figure 4.11: Comparison of hourly mean use of district heating during 2016.

There are both similarities and differences between model and measured values. The main difference occur during early morning where the measured use of district heating decreases while the use of district heating increases in the model. One theory behind the early morning differences is that in reality the temperatures might be allowed to drop during the night. That would also explain the increased use of district heating that starts around 6 am in the morning. The other main difference occur during the afternoon around 4 pm where the model uses less district heating compared to measured data. In the model the restaurants are assumed to ventilate less during 2 pm to 5 pm, this might not be the case in reality.

The main similarities are the two peaks that occur two times a day. The first one around lunch and second one in the evening. It is a positive thing that the model follows roughly the same heating pattern as reality. It is an indicator that the daily variation of loads have been estimated fairly well.

4.3.4 Conclusion

The apartment part of the building behaves quite nicely with reasonable indoor temperatures. The indoor temperatures for the restaurants are reasonable most of the year, but the model is not reliable for the coldest days. It is most likely the ventilation in the restaurants that is overestimated during these days rather than the heating system that is underestimated. This based on that the ventilation is the main loss in the restaurants when the dip in indoor temperature occurs and that the building in total already use more district heating than according to measured values for this period of time.

It would be possible to let parameters, like air flows through the thermal envelope, to be varying dependent on temperature and wind speed in order to achieve better correspondence. The main purpose of the model is however to catch the annual energy use of the building. The high need for heating at the coldest days are therefore disregarded as there are other days were the need for heating is underestimated.

4.4 Sensitivity analysis

As noticed in Section 4.2, many assumptions have been made regarding input data to the model. In order to investigate how the assumptions affect the calculated energy use, a sensitivity analysis has been performed. The parameter that has been hardest to estimate is ventilation. Hence, ventilation will be tested in the sensitivity analysis. Further the indoor temperature in the storage areas and restaurants are rather insecure parameters as no measurements have been made on site. Indoor temperature in general will therefore be tested in the sensitivity analysis. Last, the heat capacity of the building is quite roughly calculated and is a parameter which easily gets in the background in energy calculations. Hence, the thermal inertia will also be included in the sensitivity analysis. Table 4.7 shows how the parameters are changed in the sensitivity analysis.

Table 4.7: Parameters tested in sensitivity analysis.

Parameter	Change	Acronym
Ventilation	10 % increased air flow in apartments	[1.1 R_a A]
	10 % decreased air flow in apartments	[0.9 R_a A]
	10 % increased air flow in restaurants	[1.1 R_a R]
	10 % decreased air flow in restaurants	[0.9 R_a R]
Set point temperature	From 22 °C to 21 °C in apartments	[21 T_{in} A]
	From 20 °C to 21 °C in restaurants	[21 T_{in} R]
	From 12 °C to 21 °C in storage area	[21 T_{in} S]
Thermal inertia	Heat capacity increased by 50 %	[1.5 C]
	Heat capacity decreased by 50 %	[0.5 C]

Note that most of the changes occur in all apartments, restaurants or storage area separately. The difference in size of these areas needs to be considered when analyzing the results. Table 4.8 shows the floor area of apartment areas, restaurants and storage areas. The heated area not showing in the table is belonging to the staircases.

Table 4.8: Total floor area of apartments, restaurants and storage.

Zone	Floor area (m^2)	Percentage of total heated area (%)
Apartments	1190	68
Restaurants	243	14
Storage	172	10

The results will be presented in absolute difference and percentage of total energy use compared to the initial modelled case. Table 4.9 shows the results of the sensitivity analysis.

Table 4.9: Results from sensitivity analysis.

Change	Absolute difference (kW h)	Difference in percentage (%)
[1.1 R_a A]	5090	3
[0.9 R_a A]	-4870	-3
[1.1 R_a R]	4720	3
[0.9 R_a R]	-4870	-3
[21 T_{in} A]	-10150	-5
[21 T_{in} R]	7850	4
[21 T_{in} S]	26540	14
[1.5 C]	-930	0.5
[0.5 C]	4066	2

It is interesting that a 10 % difference in exhaust air flow for the restaurants and all the apartments, have almost an equal result on the total energy use, even though the apartments cover a floor area almost five times the size of the restaurants. It should however be noticed that the original exhaust air flow per area is significantly higher in the restaurants than in the apartments. A change of 1 °C in set point indoor temperature for the apartments almost corresponds to a 1 °C in set point indoor temperature for the restaurants regarding energy use. A raise in set point temperature by 9 °C in the storage area leads to the largest difference in energy use. A 50 % reduction of the building's heat capacity leads to a larger difference in energy use than a 50 % increase of the building's heat capacity.

The results from the sensitivity analysis show that the ground floor is more sensitive that the upper floors. The assumptions made regarding ventilation and indoor temperature in the ground floor have a large impact on the energy use.

5 Energy use in current building

In the following chapters, all result presented derives from the Simulink analysis or other calculations. The measured data presented in the previous chapters has only been used for calculating the heating of tap water and for validating the model of the building in its current condition. As seen in the sensitivity analysis (Section 4.4) the estimations made in the input data influences the results. Hence the results should be considered as the most likely case rather than the actual case.

Table 5.1 shows a summary of the current building's energy use, according to simulations and estimations. The heating of tap water, facility electricity and heated floor area are estimated (calculated) values while the space heating demand derives from simulations.

Table 5.1: Summary of the current building's energy use for 2016.

Tap water	61500	kW h
Space heating demand	187300	kW h
Facility electricity	25600	kW h
Total energy use	274500	kW h
Heated floor area	1749	m^2
Total energy use	157	$kW h/m^2$

The first figure (Figure 5.1) show the balance between the energy entering and leaving the building. It also provides information of what is causing the gains and losses. Note that the gain "people" also include heating gains from tap water usage and the usage of the gas-stove.

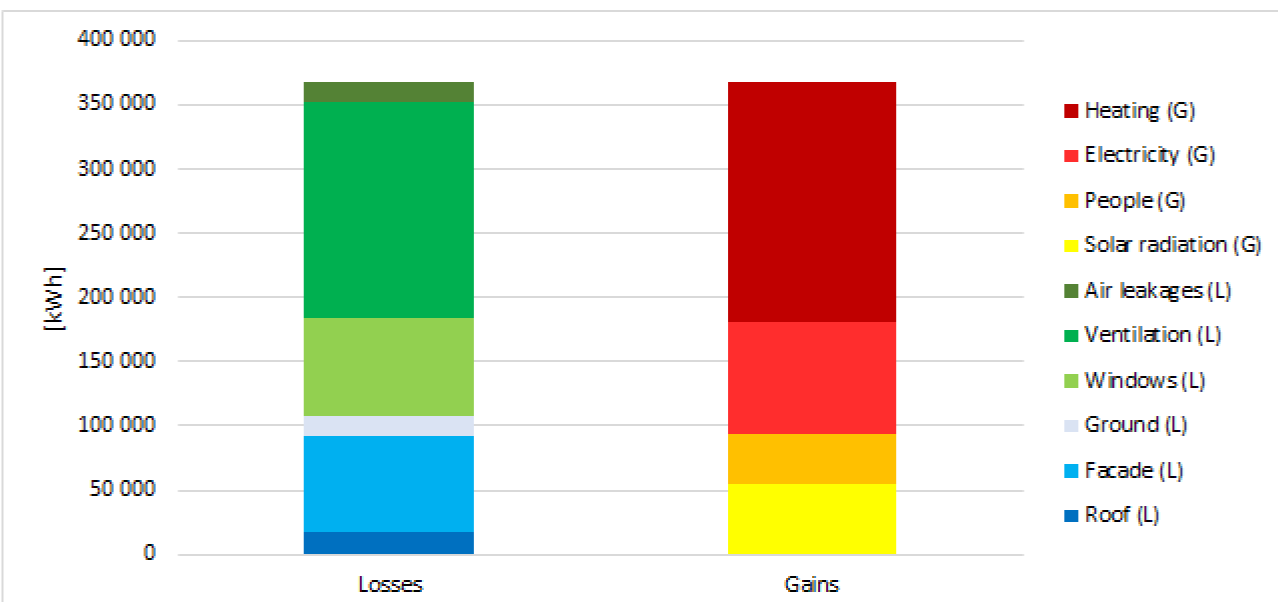


Figure 5.1: Energy balance for the whole building for the climate of 2016. (G) denotes gains and (L) denotes losses.

The main losses are from ventilation, windows and the façade. The main gains come from radiators and electrical appliances. In Figure 5.2 a more detailed view of the losses is presented. The figure also shows how the losses varies for the different temperature zones. Note that the losses are described in kW h. This means that the areas of the parts and temperature zones affects the size of the losses. As an example, the ventilation losses for the attic apartments and storey two and three are equally large in $\mathrm{kW\,h/m^2}$, but as the total area of storey two and three is greater than the attic floor, so is the loss.

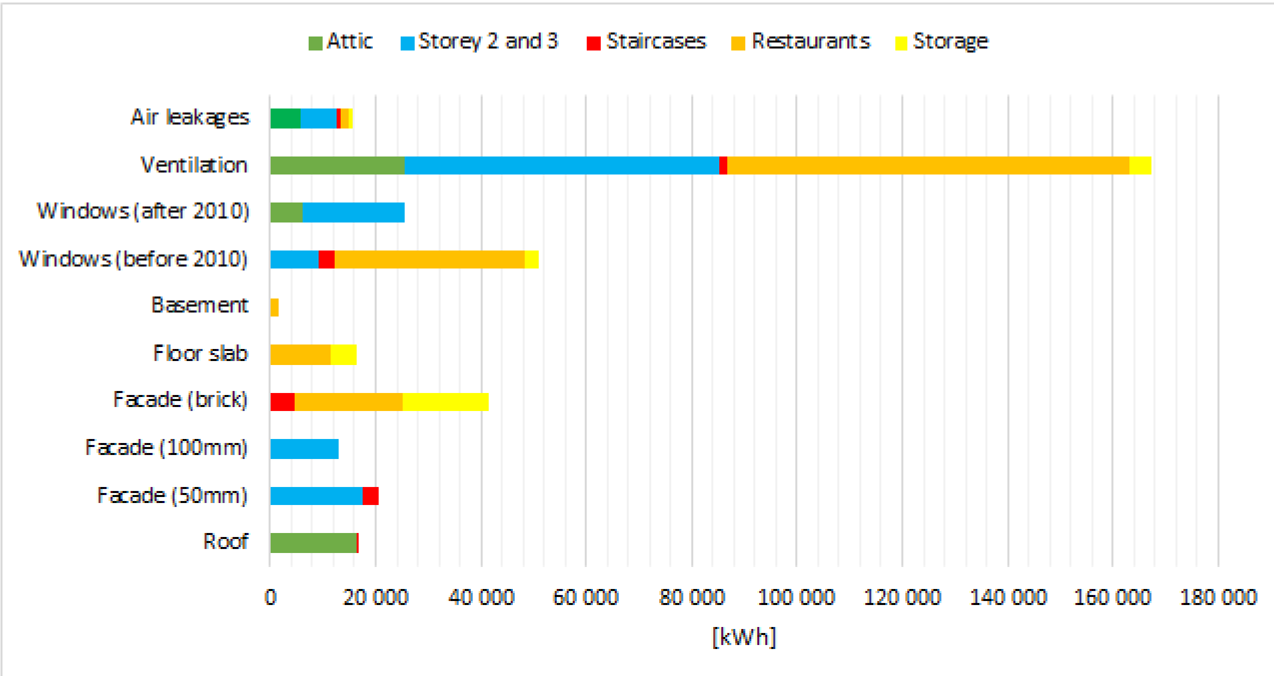


Figure 5.2: Losses for the whole building, divided into temperature zones, climate of 2016.

As already stated, the major loss is ventilation. In Figure 5.2, it becomes evident that the restaurants are responsible for the largest part of the ventilation loss, even though the floor area for the restaurants is only 65 % of the attic apartments floor area. The windows installed before the renovation 2010 is the second greatest loss, where the large restaurant windows are responsible for the largest part. The brick façade is the part of the façade causing the greatest losses, even though it only makes up about a third of the total façade area.

There is a need for heating in order to keep the indoor temperature at comfortable levels. The need for heating varies for the different temperature zone, this can be seen in Figure 5.3. However, for comparison Figure 5.4 is more interesting as it shows how much heating each temperature zone uses in relation to its floor area.

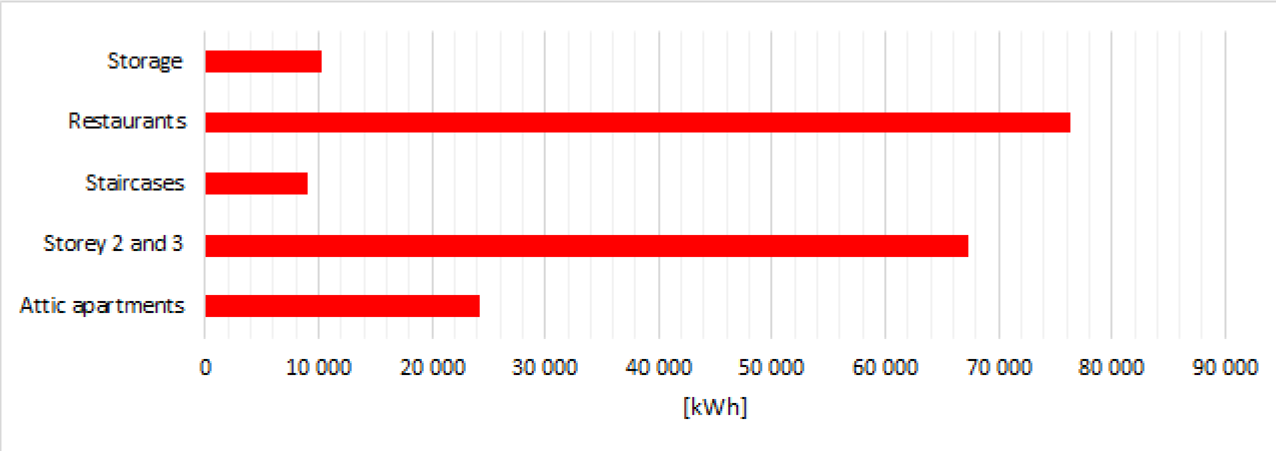


Figure 5.3: Total need for heating in each temperature zone for the climate of 2016.

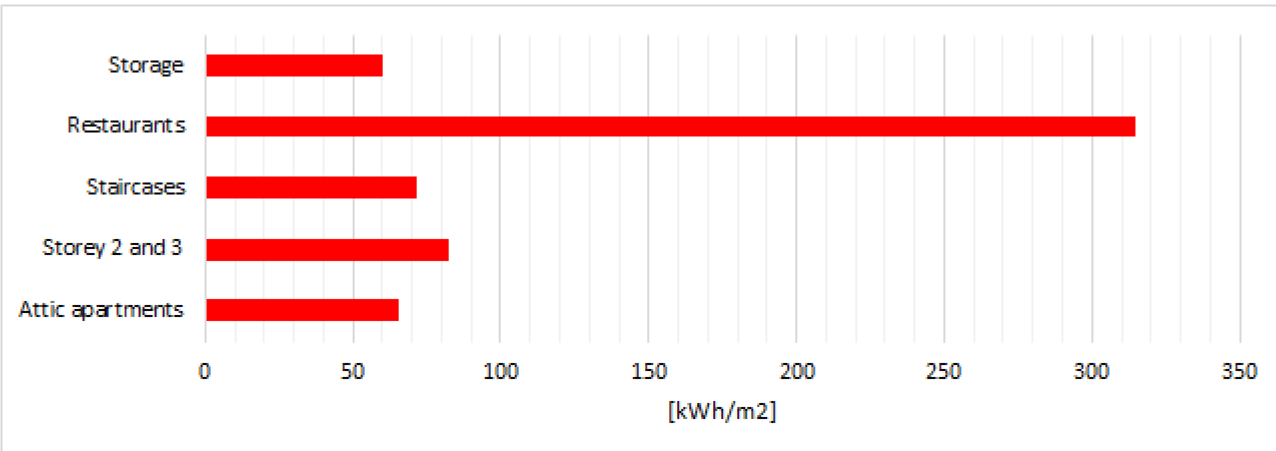


Figure 5.4: Need for heating for each temperature zone in relation to its floor area for the climate of 2016.

In Figure 5.3 it is clear that the largest need for heating occurs in the restaurants and storey two and three. In Figure 5.4 however, it becomes evident that the restaurants are far more in-efficient than storey two and three. It is also of interest to see when, during the day, that the need for heating is largest. Figure 5.5 shows the gains and losses for an average day during heating season (26/9 to 4/5) for the restaurants. Figure 5.6 shows the same information for the total apartment area. The need for heating can be distinguished as the differential between gains and losses. Note that the two figures are not in the same scale.

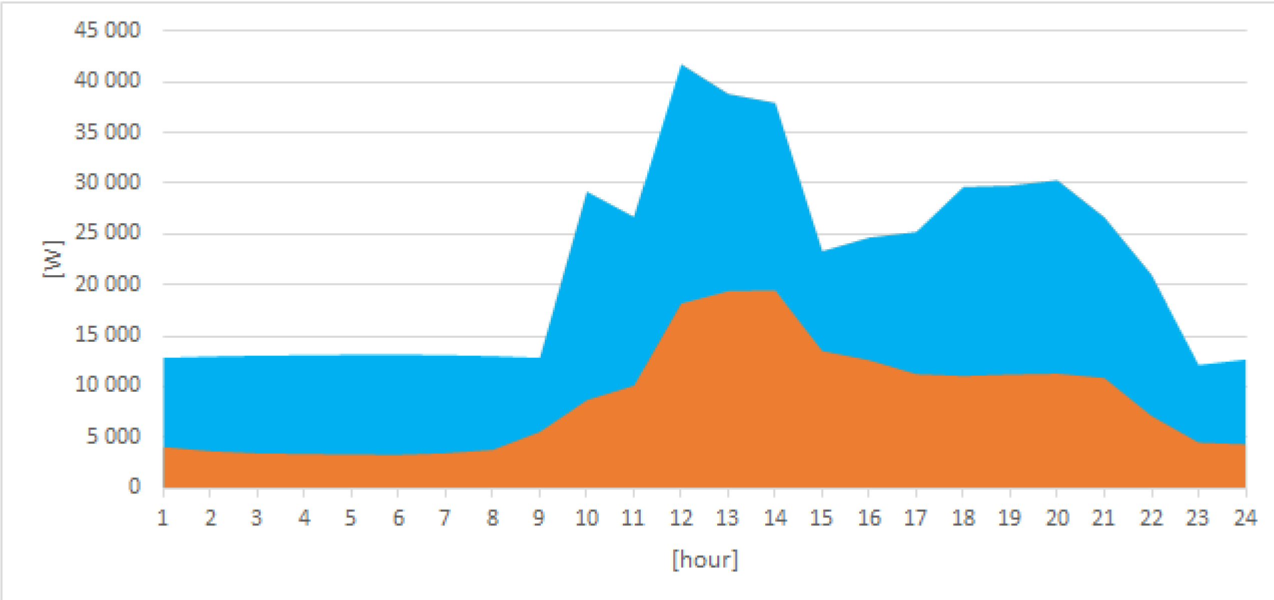


Figure 5.5: Gains (red) and losses (blue) for an average day during heating season for the restaurants.

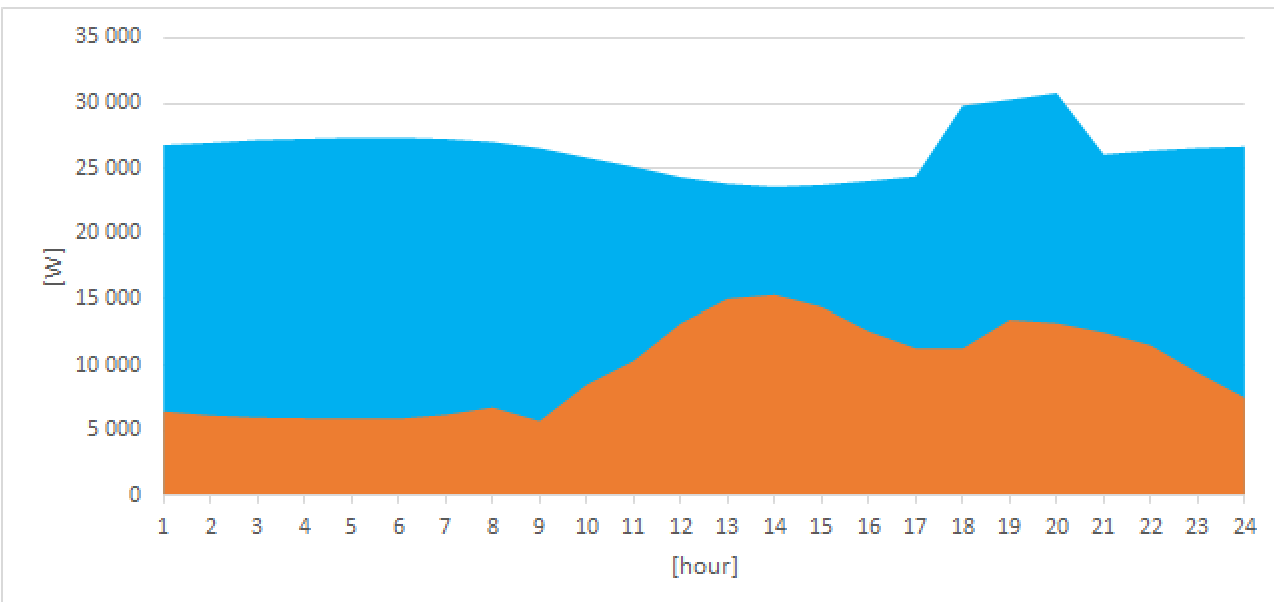


Figure 5.6: Gains (red) and losses (blue) for an average day during heating season for the apartments.

The need for heating in restaurants is largest during mid day and evening. The two peaks in losses that occur during the day is due to ventilation. The peak in gains that occurs during mid day for the restaurants is mainly due to increased electricity usage, increased amount of lunch guests and solar radiation through windows. The need for heating in the apartments is largest during night. The drop in losses decreases during the day as the temperature rises. The peak in losses during evenings is due to use of kitchen fans. The gains increases during mid day due to solar radiation through windows and during the evenings as the electricity use increases.

6 Normalising the building

In Chapter 5 it appears as if the restaurants have a huge effect on the building's usage of district heating while the storage areas use of district heating is more similar to the rest of the temperature zones, even though they both are situated in the ground floor. It seems like the different activities have a large effect on the building's use of district heating. In order to investigate this, the building has been "normalised" by modelling the ground floor as apartments. The following chapter explains what parameters that have been changed and shows a comparison between the normalised and current building. Further, the normalised building has in one case been modelled with a cold attic. A comparison is then made between the normalised building and the normalised building with a cold attic.

6.1 Parameters affected

The purpose of normalising the building is to investigate the occupancies effect on use of district heating. Hence, only parameters influenced by the activities in the building are changed. The building parts are however left in their current state. This means that the large display-windows are still in place. The floor plan of the ground floor is modelled similar to storey two and three.

For the ground floor, the ventilation and heating gains from electricity is set to the same values as the other storeys. The internal gains from people is set to the same as for storey two and three. The set point indoor temperature is set to 22 °C. During summer, the heating system is off when outdoor temperatures are 15 °C or higher (see Section 4.1.3 for exact dates). The tap water usage is estimated according to Levin (2012a), that is $25\,\mathrm{kW\,h/m^2}$. Of this, 20% contributes to heating the building. The gas stove is removed from the model. One could argue that electricity usage of the water pumps would change depending on the use of district heating decrease or increase, but for simplicity, the value is the same as before.

6.2 Energy use in normalised building

This section is organized in the same way as Chapter 5. Hence, the figures show the same kind of results but for the normalised building. A text summary of the results are given after the figures.

Table 6.1: Summary of the normalised building's energy use for 2016.

Tap water	40000	kW h
Radiators	214000	kW h
Operating electricity	25600	kW h
Total energy use	279700	kW h
Heated floor area	1749	m^2
Total energy use	160	$\mathrm{kW\,h/m^2}$

Figure 6.1: Energy balance for the normalised building for the climate of 2016. (G) denotes gains and (L) denotes losses.

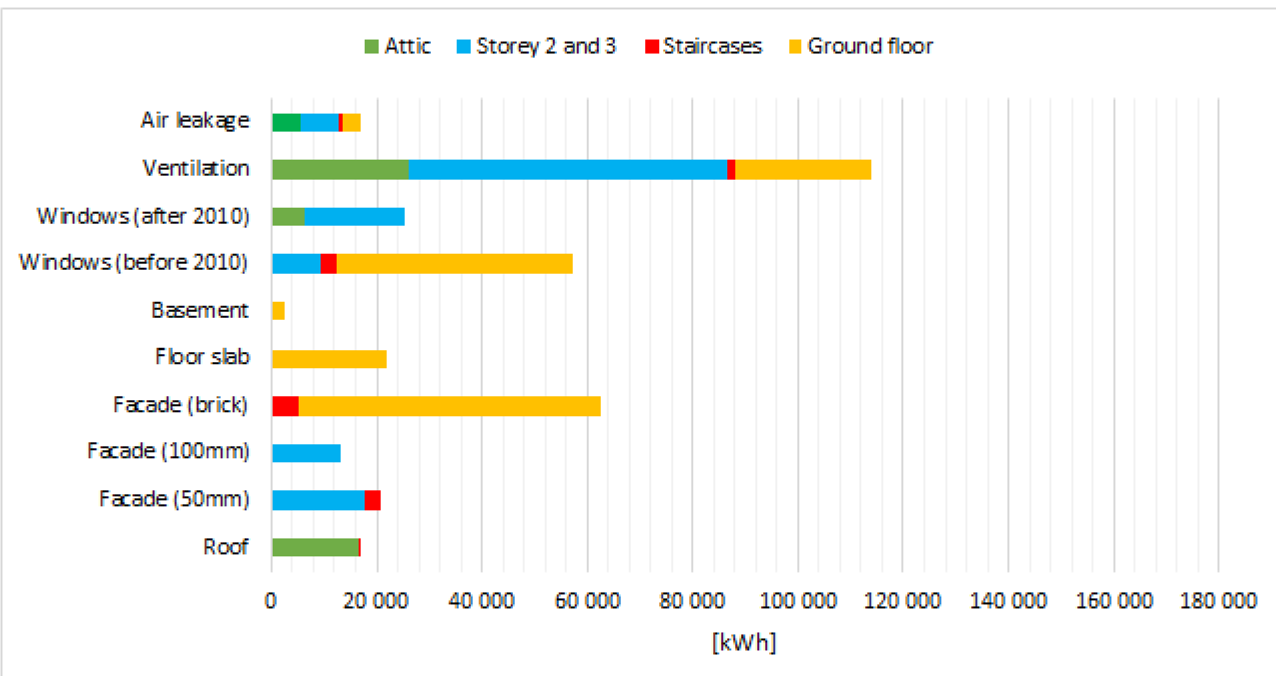


Figure 6.2: Losses for the normalised building, divided in temperature zones, for the climate of 2016.

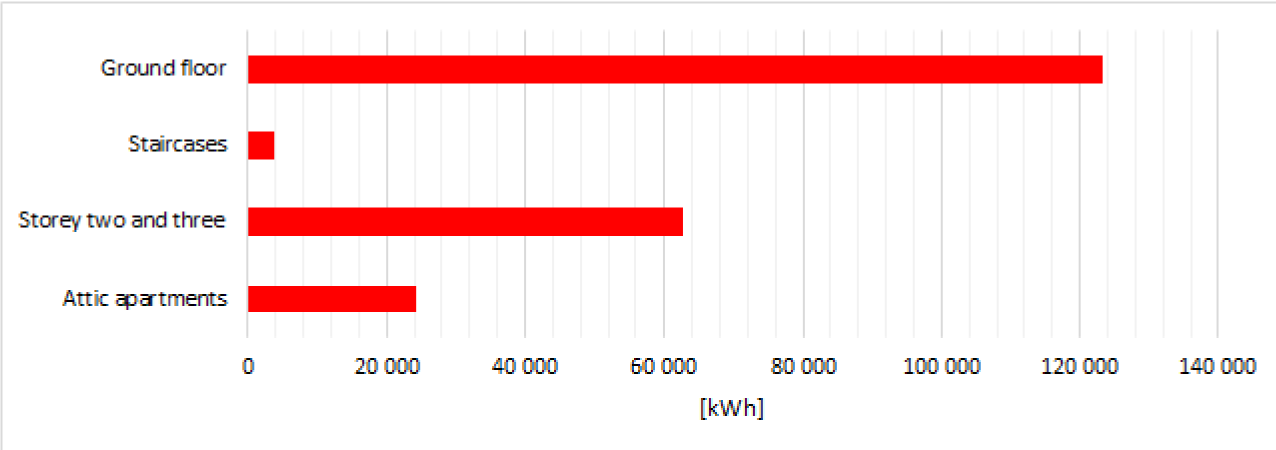


Figure 6.3: Total need for heating in each temperature zone for the climate of 2016.

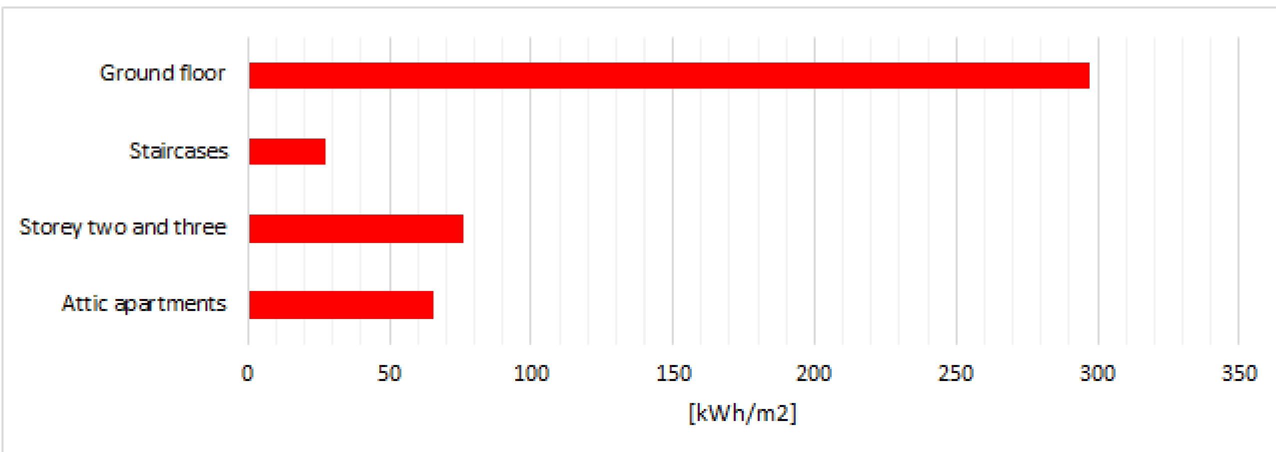


Figure 6.4: Need for heating for each temperature zone in relation to its floor area for the climate of 2016.

Figure 6.1 show the energy balance for the normalised building. The main losses are through ventilation, the façade and windows. The main addition is district heating. Figure 6.2 provides a more detailed view of the losses and information on which temperature zone they derive from. The greatest loss is ventilation followed by the brick façade and the windows installed before 2010. The brick façade is by far a greater loss than the rest of the façade together. Regarding the windows, it is the large ones on the ground floor that are responsible for the major loss. Figure 6.3 shows how the total need for heating varies for each temperature zone. Figure 6.4 shows the total need for heating for each temperature zone in relation to its floor area. It becomes evident that the ground floor has by far the greatest need for heating and is the least efficient temperature zone.

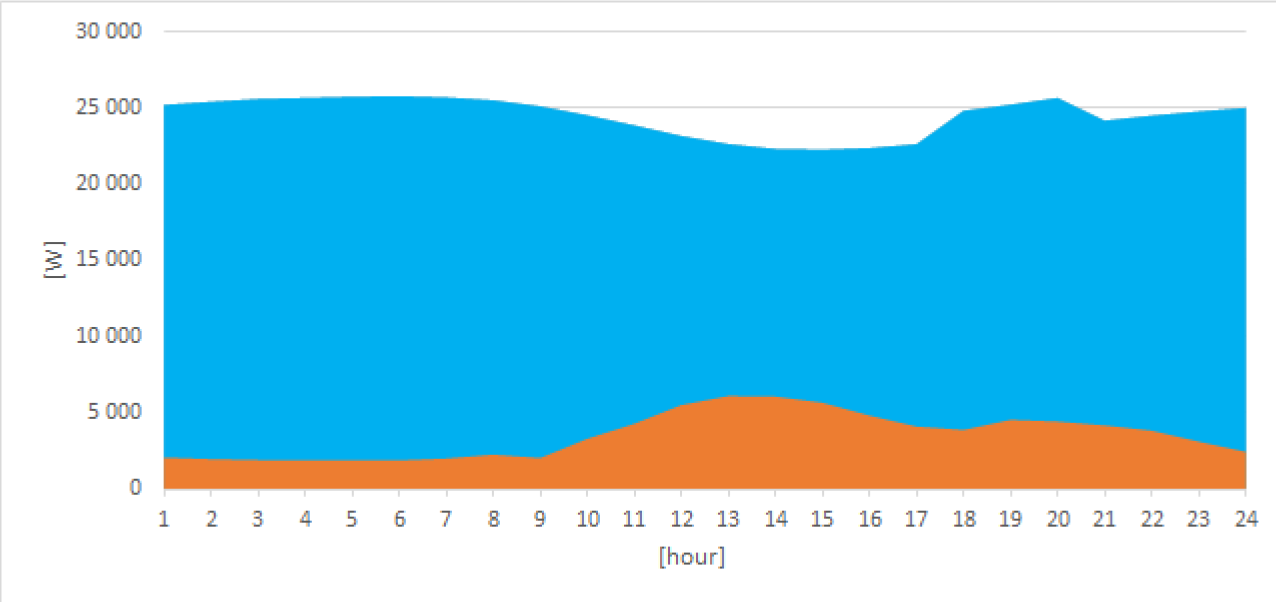


Figure 6.5: Gains (red) and losses (blue) for an average day during heating season for ground floor.

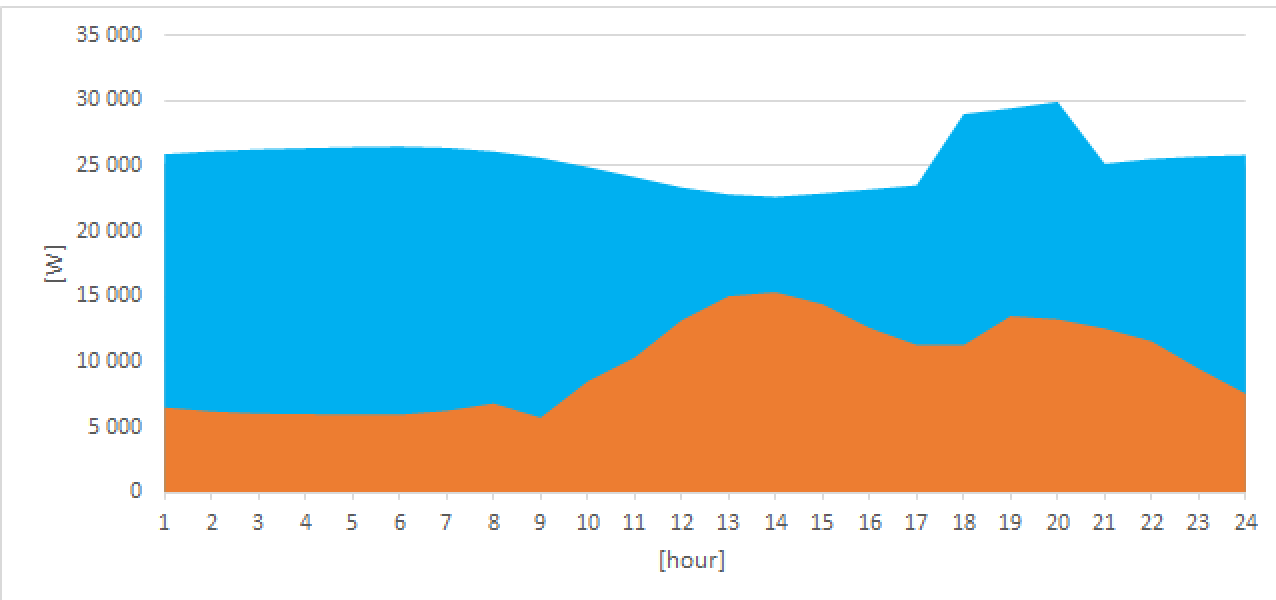
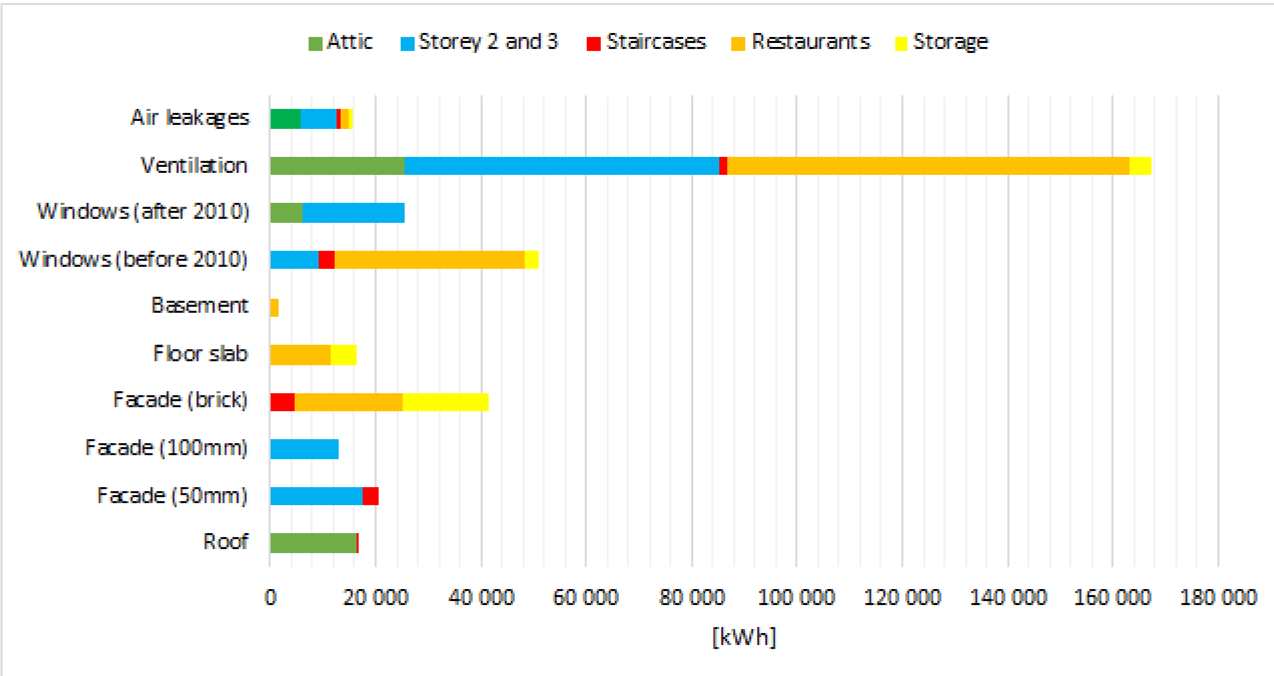


Figure 6.6: Gains (red) and losses (blue) for an average day during heating season for storey two, three and the attic apartments.

The difference in need for heating is visible in Figure 6.5 and Figure 6.6. The relative difference in losses compared to gains for the ground floor is much larger than for the rest of the floors. The losses and gains follows the same pattern for all floors. The losses are greatest during the night and during dinner hours. The gains are greatest slightly after mid day and during evenings.

6.3 Comparison between current and normalised building

To begin with, the losses are compared. This is done by having Figure 5.1 and Figure 6.1 next to each other in the same scale.



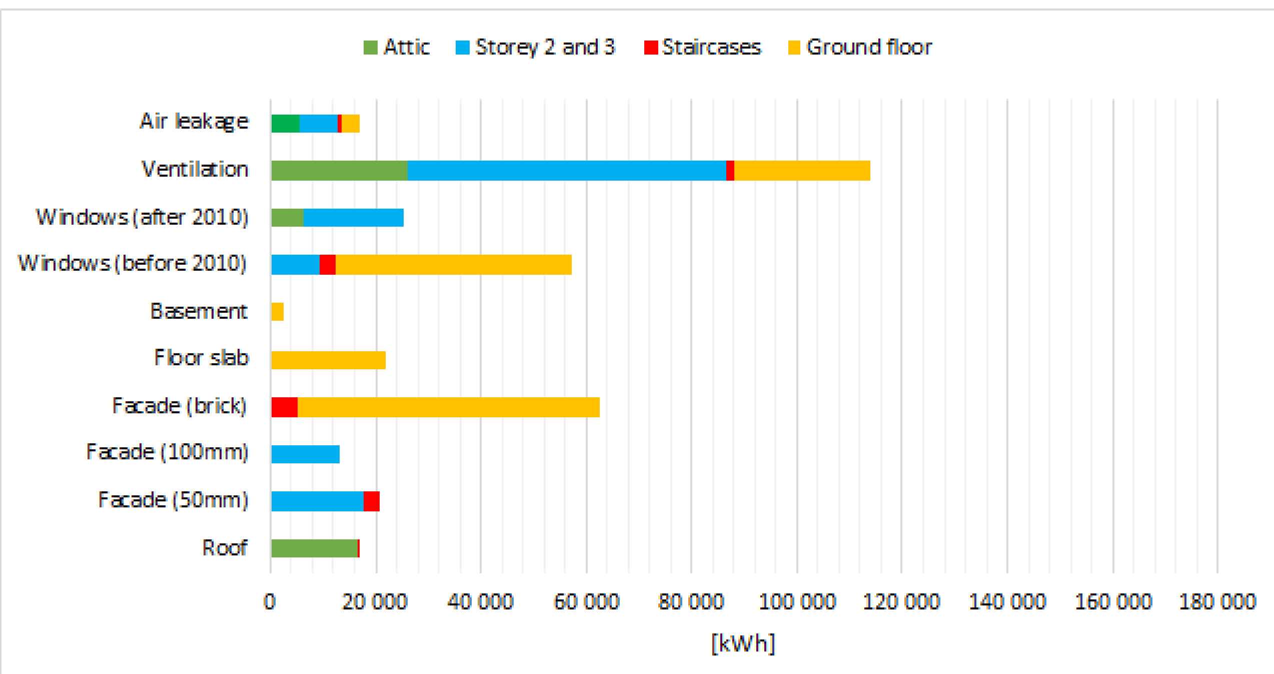


Figure 6.7: Comparison of losses for the current (top) and normalised (bottom) building for the climate of 2016.

It becomes evident that the ventilation loss in the ground floor is significantly lower in the normalised building compared to the ventilation loss for the restaurants and storage area in the current building. This primarily shows the restaurant's impact on ventilation losses. The losses through windows and the brick façade on the ground floor is however higher in the normalised building. This is most likely due to the higher indoor temperature in the normalised building, as a greater difference between in and outdoor temperature leads to larger losses, see Equation (4.1). The set point indoor temperature for the storage area in the current building is 12 °C. In the normalised building, the same area is occupied by apartments with a set point temperature of 22 °C. The losses through the floor slab is also higher in the normalised building, which most likely has the same explanation.

Figure 6.8 shows a comparison between the energy balances for the current and normalised building.

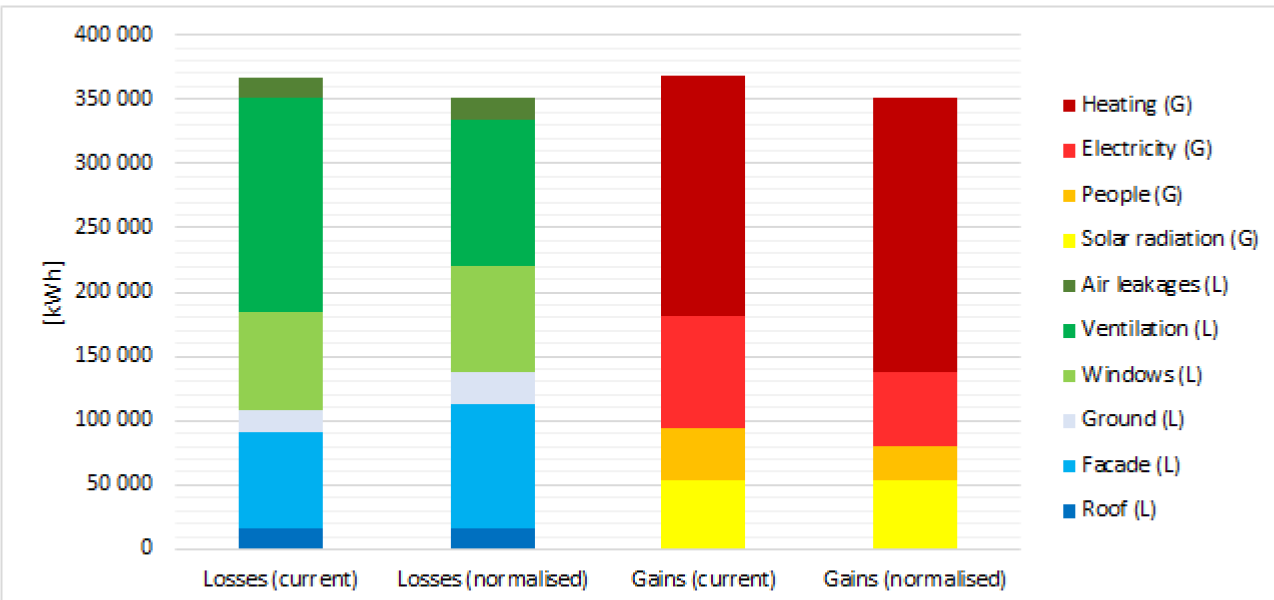


Figure 6.8: Comparison of energy balances for current and normalised building.

Even though the total loss is lower in the normalised building, the need for heating have increased. This is due to that the gains from people and electricity have decreased significantly. The need for heating in the different temperature zones for the current and normalised building is compared in Table 6.2. Note that for the current building, the ground floor denotes the need for heating in restaurants and storage areas together.

Table 6.2: Comparison in need for heating between current and normalised building.

	Current building [kW h]	Normalised building [kW h]
Ground floor	86700	123200
Staircases	9000	3900
Storey two and three	67400	62700
Attic apartments	24200	24300

It is clear that the largest difference in need for heating occurs in the ground floor, where the normalised building needs 36 500 kW h more than the current building. However, the need for heating in the adjacent temperature zones is in total around 10 000 kW h less than in the current building. This is due to that the ground floor's indoor temperature is higher in the normalised building than in the current building. Table 6.3 shows a comparison of the energy use in the current and normalised building.

Table 6.3: Comparison of the current and normalised building's energy use for 2016.

	Current building	Normalised building	Unit
Tap water	61500	40000	kW h
Radiators	187300	214000	kW h
Operating electricity	25600	25600	kW h
Total energy use	274500	279700	kW h
Heated floor area	1749	1749	m^2
Total energy use	157	160	$kW\,h/m^2$

Even though the need for heating (radiators) has increased, the heating of tap water has decreased for the normalised building. In total energy use, the two cases are quite similar.

6.4 Normalised building with cold attic

A common measure to reduce the total energy use per meter squared in old buildings is to remake the attic into apartment. This was done in the current building in 2010. It is of interest to study how a renovation of the attic can affect the building's energy use. Therefore a comparison is made by modelling the normalised building with a cold attic.

6.4.1 Parameters changed

The ventilation in the cold attic varies depending on wind speed, see Table 6.4. For wind speeds in between table values, the air exchange rate is interpolated. For wind speeds over the maximum table value, air exchanges remain at its maximum value. The air exchanges rates were suggested by Wahlgren (2017). The wind intervals were estimated by the author. The external roof in the cold attic is estimated to be uninsulated, only consisting of metal sheets and wooden boards (U-value of 3.61 $W/(m^2\,K)$).The attic floor structure has 200 mm of insulation. This gives an U-value of 0.18 $W/(m^2\,K)$. There is also an air leakage modelled between the attic and storey three, which is estimated to 0.032 $l/(s\,m^2)$. The operating electricity changes for the cold attic. The total exhaust air flow is lower, hence less electricity is needed for fans. The floor heating in the attic disappears and the electricity needed for heat pumps is estimated to be slightly lower. The total value for operating electricity is seen in Table 6.5. The heating of tap water also decreases. The new value for heating of tap water is calculated according to Levin (2012a) and can be seen in Table 6.5.

Table 6.4: *Relation between wind speed and air exchanges in cold attic.*

Wind speed [m^3/s]	Air exchanges [1/h]
0	0.2
2.67	0.7
6	1.4

6.4.2 Comparison of normalised building and normalised building with a cold attic

The results when comparing the energy use in the normalised building with attic apartments and the normalised building with a cold attic is shown in Table 6.5.

Table 6.5: Comparison of the normalised building with cold attic's and normalised building's energy use for 2016.

	Cold attic	Normalised building	Unit
Tap water	30800	40000	kW h
Radiators	198100	214000	kW h
Operating electricity	18415	25600	kW h
Total energy use	247300	279700	kW h
Heated floor area	1374	1749	m^2
Total energy use	180	160	kW h/m^2

In the end, it differs 20 kW h/m^2 in favor to the normalised building. Hence, it is clear that the normal case is more energy efficient than the case with a cold attic. For this particular case, the remaking of attic into apartments is extra beneficial as the ground floor is very energy in-efficient. By having a well insulated roof and modern windows, the attic apartments are far more energy efficient than the ground floor apartments and therefore energy use per heated area for the total building is improved.

7 Measures for improved energy efficiency

One part of the purpose is to evaluate different measures for improved energy efficiency. This is done by performing a parameter study on the normalised building. The normalised building is chosen in order for the parameter study to be as general as possible.

Based on Figure 6.2, there are mainly three parameters that are responsible for most of the losses. These are ventilation, old windows and the brick wall on the ground floor. The old windows can further be divided into single pane and double pane windows. The display-windows on the ground floor are single pane. The smaller windows on the ground floor and the windows towards the yard are double pane. Table 7.1 shows all measures tested in the parameter study.

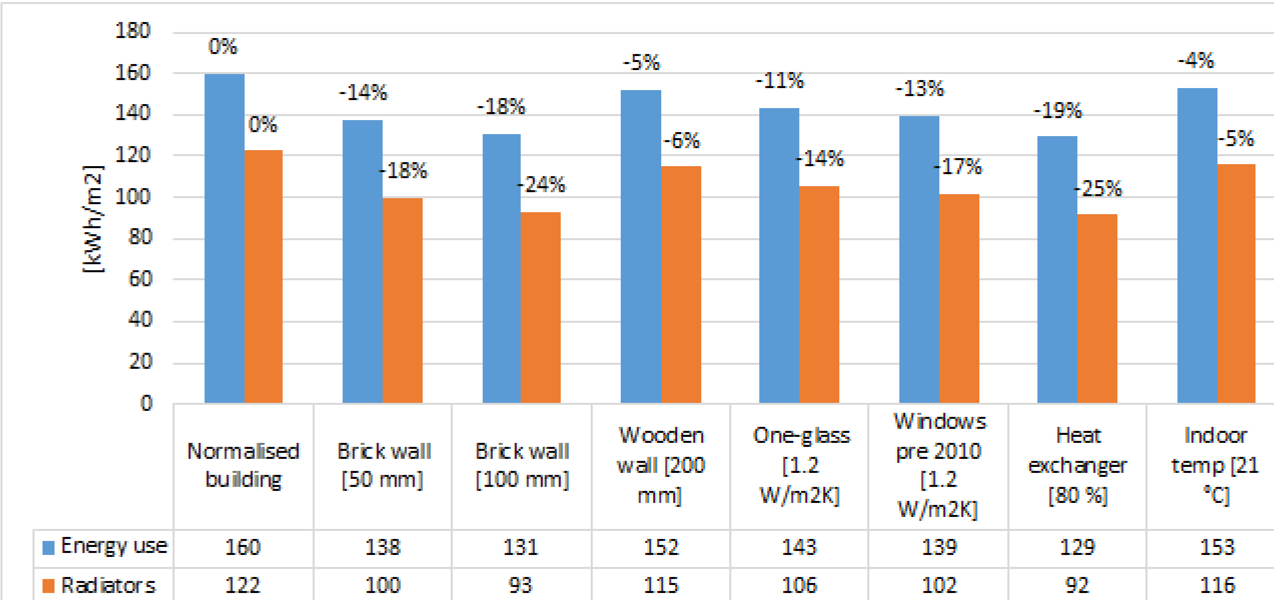
Table 7.1: Measures tested in the parameter study.

Parameter	Measure
Ventilation	Install a heat exchanger [80% utilization factor]
Windows	Change single pane windows [U-value: 1.2 $W/(m^2\,K)$]
	Change one and double pane windows [U-value: 1.2 $W/(m^2\,K)$]
Brick wall	Add inside insulation [50 mm]
	Add outside insulation [100 mm]
Wooden wall	Add outside insulation [200 mm]
Indoor temperature	Lower to 21 °C (from 22 °C)

A heat exchanger system heats the supply air with the exhaust air. For the parameter study the utilization factor is set to 80%. The leakages, airing through open windows and extra ventilation from kitchen fans are not affected by the heat exchanger. The heat exchanger is only active when the outside temperature is under 15 °C. The area of the windows remains the same, it is only their U-value that changes. There are two options for the brick wall. It is either insulated on the inside or on the outside. The inside option result in less insulation compared to the outside option as the risk for frost damages is larger when insulating on the inside. Inside insulation often results in more thermal bridges, this is however not considered in the parameter study. The wooden wall currently have 100 mm of insulation towards the street and 50 mm of insulation towards the yard. The measure tested is to replace that insulation with 200 mm all around the building. All insulation added is assumed to have a thermal conductivity of 0.037 $W/(m\,K)$. A consequence of reducing transmission losses is that the indoor temperature can be lowered. This is due to that the experienced temperature increases as the temperature of indoor surfaces increases (Bean, 2012).

7.1 Results

Figure 7.1 shows how each change of parameter affects the need for heating and energy use. As expected, increasing the insulating performance of the brick wall and old windows has a large effect on the normalised building's energy use. Further insulation on the wooden wall is about equally good as lowering the indoor temperature with 1 °C. Installing a heat exchanger has however the largest effect on energy use.



	Normalised building	Brick wall [50 mm]	Brick wall [100 mm]	Wooden wall [200 mm]	One-glass [1.2 W/m2K]	Windows pre 2010 [1.2 W/m2K]	Heat exchanger [80 %]	Indoor temp [21 °C]
Energy use	160	138	131	152	143	139	129	153
Radiators	122	100	93	115	106	102	92	116

Figure 7.1: Parameter study on measures for improved energy efficiency. The data series "Radiators" shows how the need for heating is affected of changing the parameters. The data series "Energy use" shows how the total energy use (radiators, heating of tap water and operating electricity) of the building is affected .

Figure 7.2 shows two different cases compared to the normalised building. In the first cases all the best transmission measures are included. These are 100 mm of insulation on the brick wall, 200 mm of insulation on the wooden wall and replacing all windows from before 2010. The lowering of indoor temperature is also included as this measure is more of a consequence of lowering transmission losses. The second case includes all measures in the first case plus the heat exchanger.

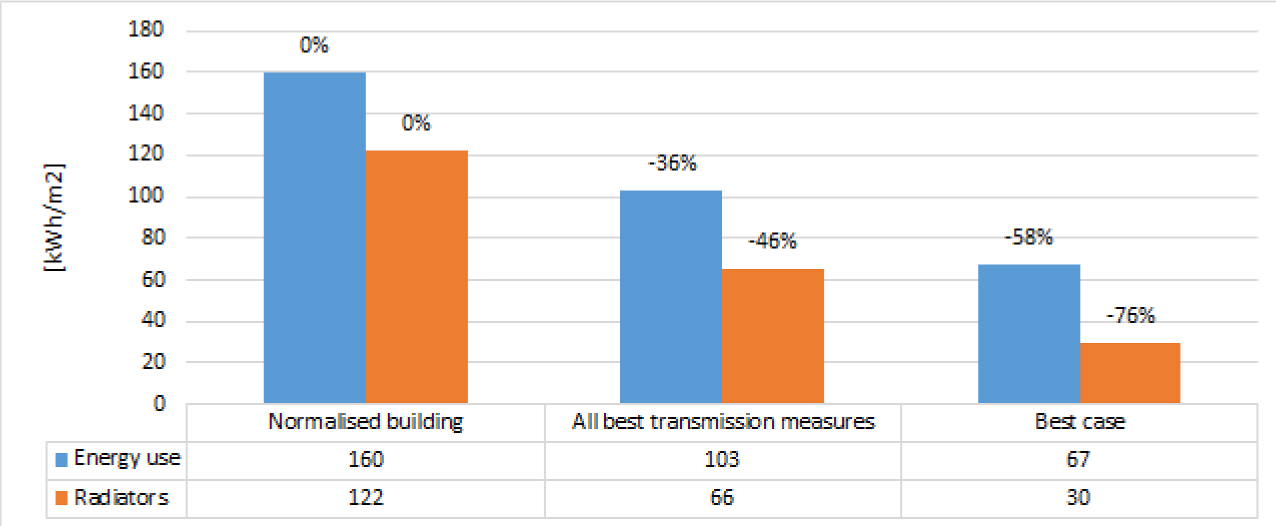


Figure 7.2: Two cases for improving the normalised building. The data series "Radiators" shows how the need for heating is affected of changing the parameters. The data series "Energy use" shows how the total energy use (radiators, heating of tap water and operating electricity) of the building is affected.

By applying all transmission measures (the first case) the energy use can be lowered with 33 %. This corresponds to 91 400 kW h or 52 kW h/m^2. The best case possible (second case) the energy use is lowered with 58 % and the need for heating is lowered with 76 %. For this case the heating of tap water and operating electricity have more effect on the energy use than the need for heating. The decrease in energy use corresponds to 162 400 kW h or 93 kW h/m^2.

8 Discussion

The chapter begins with a general discussion about the method used in the thesis. The major part of this chapter is however going to treat sources of errors.

8.1 Method

It became evident throughout the work that more measurements and dialogue would be needed to make a reliable model over the actual building. Especially indoor temperatures must be measured for each zone in the building, as this has a great influence on the results. After indoor temperature, ventilation is a difficult parameter to approximate, especially for restaurants. An open dialogue with the restaurant owners and data over the fans and their settings would have increased the exactness of air flows and run times for the kitchen fan. It would also have been useful with information about the heating control system, if it reacts to indoor or outdoor temperatures and if its programmed to save energy during night time.

The normalising of the building can be discussed. The purpose was to investigate how the activity inside the building changed the energy use, and therefore the different building parts was not changed. It is however possible to argue that the large display windows on the ground floor is a consequence of the previous activity and could have been changed in order to match the quality of windows of the rest of the building. If the windows had been changed, the normalised building would have been more realistic. The advantages with only changing the soft parameters (ventilation, indoor temperature, tap water use etc.) were that these parameters were the most roughly estimated ones and it made it possible to compare the performance of the thermal envelope for the two cases.

It would have been interesting to model the building with other kind of activities on the ground floor as well, for example regular stores and offices. This type of activities are commonly found in these type of buildings. The parameter study was only performed in the normalised building due to lack of time. It can be questioned how general the results are from only studying one type of building. The scope of the thesis, and the project at Chalmers, is including all buildings built before 1945. From this thesis, it is not possible to draw general conclusions for a scope that wide. It is, however, possible to draw some conclusions about "Landshövdingehus", as the construction method for these buildings were quite standardized, and especially the ones with uninsulated ground floors.

8.2 Possible source of errors

Simulations are supposed to mimic the reality. When information of reality is insecure or lacking, the best possible assumption is applied. In this section the reader gets an understanding of when and why the model might differ from reality.

8.2.1 Floor areas

For the attic storey, CAD-drawings where provided by Skärgårdens byggteknik. There is no guarantee that the drawings provided are completely accurate. The storeys not included in the CAD-drawings where inserted into CAD as pictures and scaled according to some known measurements. This is for example a wall or the width of the building. However, as the energy use of the building is compared between models rather than with measured values, the floor areas are not of that much importance. If energy use per meter squared is compared to, for example, an energy declaration, the areas used needs to correlate.

8.2.2 Construction

Many parts of the construction are not specified on drawings. In these cases, estimations have been made based on literature and sightings from field visits. If a part of the building is not mentioned in any documentation of renovations and nothing was seen during field visits that indicates else wise, it is assumed to be original. For parts of the construction in between temperature zones, this is not very important, as the temperature difference between temperature zones is smaller than between temperature zones and outside. The ground plate and brick walls are example of construction parts that are assumed to be original. If there is something insulating on the interior of these construction parts, that would be a considerable source of error. Regarding the documented construction parts, the exact material properties are lacking. The assumed values do probably not fully correlate with the real values.

8.2.3 Data from Göteborg Energi

The data provided is most likely of good quality. However some important assumptions were made when separating heating of tap water from total usage of district heating. The heating of tap water per day was derived from the total use of district heating during summer. Possible variations of heating in tap water over the seasons is hence neglected. In reality, factors like supply water temperature and air temperature around the hot water tank affects the amount of heating needed. Further, habits for using hot tap water might change over the seasons. These sources of error have mainly two different impacts. First, the annual heating of tap water might be under or overestimated depending on whether the usage of hot tap water is greater or lesser during summer. Secondly, as the usage of tap water is very time specific, if the habits of using it differs between winter and summer, the estimated average hourly heating of tap water per day Figure 3.6 could be deluding. Consequently, Figure 4.11 could be misguiding in how the heating from radiators varies during the daily hours, as these values derives from the result of subtracting the estimated heating of tap water from the total use of district heating. Another source of error that could affect the average hourly values of heating during the day is the change between summer and winter time in Sweden. During summers, the time is mowed forward one hour in Sweden. In the data from Göteborg Energi, it is not clear whether this is considered or not.

8.2.4 Weather data

All climate data is from a station in central Gothenburg except the cloudiness and long wave radiation. Data of cloudiness is from the coastline of Gothenburg. The data of long wave radiation is from Växjö, a town placed about 200 km east, south-east of Gothenburg. It is a problem that the global solar radiation and the cloudiness is not measured at the same geographical location. The global solar radiation is divided into diffusive and direct radiation mainly based on cloudiness. This means that in the model, direct solar radiation can be labeled as diffusive radiation, if it was cloudy at the coast and clear sky over the city when the data was measured. In the model, this effects the solar heat load as the windows transmittance differ between direct and diffusive radiation. Generally, more of the diffusive radiation is assumed to enter the room as the transmittance is not affected by angle of incidence. As a summation, if direct radiation is assumed to be diffuse radiation the modelled heat load will increase. For the opposite, the heat load will decrease.

The weather station is centrally placed in Gothenburg. This increases the reliability of the data as the temperature is often higher in urban areas.

8.2.5 Temperature zones

The indoor temperature is assumed to be constant inside each temperature zone. In reality, the temperature varies between apartments depending on direction of the windows, number of people in each apartment etc. This is important when considering solar heat load. In reality, the indoor temperature in apartments with windows in the direction of the sun is only affected by the solar heat load. In the model, the indoor temperature of whole storeys are affected by the solar heat load from one direction. Regarding energy use, this is most likely beneficial as a whole storey can benefit from the solar gains through the windows of one apartment.

8.2.6 Equations used for modelling

The equation used for modelling ventilation and leakages is a highly simplified version of the reality. Regarding ventilation, the equation works as if the exhaust fan was constantly regulating frequency in order to keep the exhaust flow constant. In reality, the fans are set on a single frequency, and the airflow changes depending on the inflow resistance and difference in indoor and outdoor pressure. This means that the exhaust flow changes depending on wind speed and wind direction as well as openings in the thermal envelope. Regarding leakage, the problems are similar as for ventilation. When opening the window, the air flow depends on the size of the opening and difference in indoor and outdoor pressure. A further factor is if two windows are opened at the same time and a draft appears. In the model, a constant increase of airflow is added when indoor temperatures becomes over 24 °C. Hence, This source of error should especially be considered when analyzing the indoor temperatures during summer and ventilation losses during windy periods of the year

8.2.7 Input data in general

It is important to realize that the input data used from Levin (2012a) is meant to imitate the yearly behaviour of a building. For example, according to Levin (2012a), the average person is home 14 h a day. Of course, in reality this number varies depending on the day of the week or on whether it is summer or winter. For the use of district heating, it would for example be beneficial if people were home more during heating season and away more during summers. The opposite would instead be unfavourable. However, it is beneficial that the 14 h where people is assumed to be home is always occurring from afternoon til morning, as this is the period of the day when outdoor temperatures are the lowest and heating need for apartments the greatest. On the opposite, the input data from Göteborg Energi is provided on an hourly basis. This means that the gains from the use of electricity is varying on an hourly bases. The differences in electricity use between winter and summer is therefore included in the model. This is most likely beneficial for the energy use as the use of electricity is slightly higher during heating season (see Figure 3.1).

The data given in Levin (2012a) mainly address new buildings. For the current building this has been considered by for example using a higher indoor temperature than recommended and using a higher airflow. It could however influence the result when dividing electricity between restaurants and apartments as the electricity use from Levin (2012a) derives from modern appliances.

9 Conclusions

For the current building, the ground floor is the least energy efficient floor. The first reason for this is the poor thermal properties of the concrete slab, external walls and large single pane windows. The second reason is the ongoing restaurant activity in the ground floor causing a large amount of ventilation losses. The storage areas on the other hand are only responsible for a small part of the building's total energy use, as long as the indoor temperatures in the storage areas are as low as assumed.

The comparison between the current and normalised building showed that transmission losses becomes more dominant when changing the activities from restaurants/storage to apartments. This is due to a combination of higher indoor temperatures and lower ventilation rates. The total amount of losses decreased in the normalised building, but the need for heating increased due to less internal gains. A main conclusion drawn from the comparison is that the on going activities inside the building has a large influence on the magnitude of the losses.

For the normalised building, the best measures to reduce energy use are to install a ventilation system with a heat exchanger, insulate the brick wall and install modern windows. With measures to decrease transmission losses, the total energy use can be reduced by 33 %. With measures to decrease transmission losses combined with a heat exchanger, the total energy use can be reduced by 58 %. By applying the later case, the energy use goes down to levels comparable to new buildings. As the activities inside the building have an impact on the losses, they also have an impact on the energy savings from potential renovations. For the current building compared to the normalised building, insulation measures would most likely have a smaller impact on the energy use, as the transmission losses are smaller.

General conclusions about "Landshövdingehus" is that the ground floors can account for a large use of energy compared to the other floors. Signs of energy inefficient ground floors are uninsulated brick walls and large old display windows. The ground plate also have a part in this as it was not insulated from the beginning in these type of buildings and for obvious reasons harder to additionally insulate in retrospect than for example the roof or façade.

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A Building parts used in the model

Appendix A shows all building parts used in the model.

Surface resistance

Rsi =	0,13	[m^2K/W]
Rse =	0,04	[m^2K/W]

Building parts

Facade - 100 mm insulation

Materials	*Thickness [m]*	*Thermal conductivity [W/mK]*	*[m^2 K/W]*	*U-Value [W/m^2 K]*	*Area [m²]*
Wooden panel	0,023	0	0,200		
Furring strips (Air gap)	0,028	0			
Insulation	0,100	0,037	2,703		
Plaster	0,015	0,300	0,050		
Wooden panel	0,022	0,150	0,147		
Wooden plank	0,075	0,150	0,500		
Plaster	0,020	0,300	0,067		
Total	0,232		3,666	0,261	379
Thermal bridges			15,00%	0,300	

Facade - 50 mm insulation

Materials	*Thickness [m]*	*Thermal conductivity [W/mK]*	*[m^2 K/W]*	*U-Value [W/m^2 K]*	*Area [m²]*
Metal sheet panel	0,023	0	0,100		
Furring strips (Air gap)	0,028	0			
Insulation	0,050	0,037	1,351		
Plaster	0,015	0,300	0,050		
Wooden panel	0,022	0,150	0,147		
Wooden plank	0,075	0,150	0,500		
plaster	0,020	0,300	0,067		
Total	0,182		2,215	0,419	384
Thermal bridges			15,00%	0,482	

Facade - Brick wall

Materials	*Thickness [m]*	*Thermal conductivity [W/mK]*	*[m^2 K/W]*	*U-Value [W/m^2 K]*	*Area [m²]*
Brick	0,300	0,600	0,500	1,493	400
Thermal bridges			0,00%	1,493	

Roof

Materials	Thickness [m]	Thermal conductivity [W/mK]	[m ^{2} K/W]	U-Value [W/m ^{2} K]	Area [m²]
Metal sheets	-	0	0,150		
Underlayboard	-	0			
Roof battens	0,022	0,000			
Air gap	0,045	0,000			
Insulation	0,195	0,037	5,270		
Trusses (45*240) c1200	0,240	0,000			
Plastic	0,000	0,300	0,000		
Ceiling battens	0,028	-	0,180		
Gypsum board	0,026	0,170	0,153		
Total	0,316		5,753	0,170	807
Thermal bridges			30,00%	0,221	

Innerwall - Appartment dividing wall

Materials	Thickness [m]	Thermal conductivity [W/mK]	[m ^{2} K/W]	U-Value [W/m ^{2} K]
Chip board	0,02	0,140	0,143	
2*75 mm wooden stud	0,15			
Mineral wool	0,15	0,040	3,750	
Chip board	0,02	0,140	0,143	
Total	0,19		4,036	0,248

Innerwall - Load bearing

Materials	Thickness [m]	Thermal conductivity [W/mK]	[m ^{2} K/W]	U-Value [W/m ^{2} K]
Chip board	0,02	0,140	0,143	
Studs	0,1			
Air	0,15			
Chip board	0,02	0,140	0,143	
Total	0,14		0,286	3,500

Floor structure - Original

Materials	Thickness [m]	Thermal conductivity [W/mK]	[m ^{2} K/W]	U-Value [W/m ^{2} K]
Parquet	0,015	0,140	0,107	
Dense woodfiber board	0,015	0,130		
Tongue and groove boards	0,022	0,140	0,157	
Joists, sawdust	0,15	0,080	1,875	
Tongue and groove boards	0,022	0,140	0,157	
Rendering	0,01	1,000	0,010	
Total	0,234		2,306	0,404

Floor structure - Attic

Materials	*Thickness [m]*	*Thermal conductivity [W/mK]*	*[m^2 K/W]*	*U-Value [W/m^2 K]*
Parquet	0,015	0,140	0,107	
Shingel	0,022	0,180	0,122	
Insulation board	0,05	0,040	1,250	
Tongue and groove boards	0,022	0,140	0,157	
Wooden studs, insulation	0,2	0,040	5,000	
Tongue and groove boards	0,022	0,140	0,157	
Rendering	0,01	1,000	0,010	
Total	0,341		6,804	0,143

Ground slab

Materials				*U-Value [W/m^2 K]*	*Area [m²]*
Concrete	0,2	1,7	0,118	8,500	
makadam	0,2	3	0,067	15,000	
Mark	0,2	2	0,100	10,000	
w	0,300			11,860	
A	457	d	0,330		
P	126	B	9,000		
B	7,3	L	30,000		
lambda	2	d/B	0,037		
alpha_i	8	L/B	3,333		
alpha_e	25	A/kins	0,084		
dt	0,799				
U				0,574	320

Window - standard - street

Nmbr of glass	*Diffuse sunlight*	*U-Value [W/m^2 K]*	*Area [m²]*
2+1	0,75	1,300	171

Window - Facade-lower, street, 1

Material	*Thickness [m]*	*Thermal conductivity [W/mK]*	*[m^2 K/W]*	*U-Value [W/m^2 K]*	*Area [m²]*
Glass	0,01	0,81	0,012	5,484	67

Window - standard yard

Nmbr of glass	*Diffuse sunlight*	*U-Value [W/m^2 K]*	*Area [m²]*
2	0,80	2,500	69

B Simulink model of attic apartments

Several Simulink models have been used in the thesis. This Appendix is displaying the attic zone of the model over the actual building.

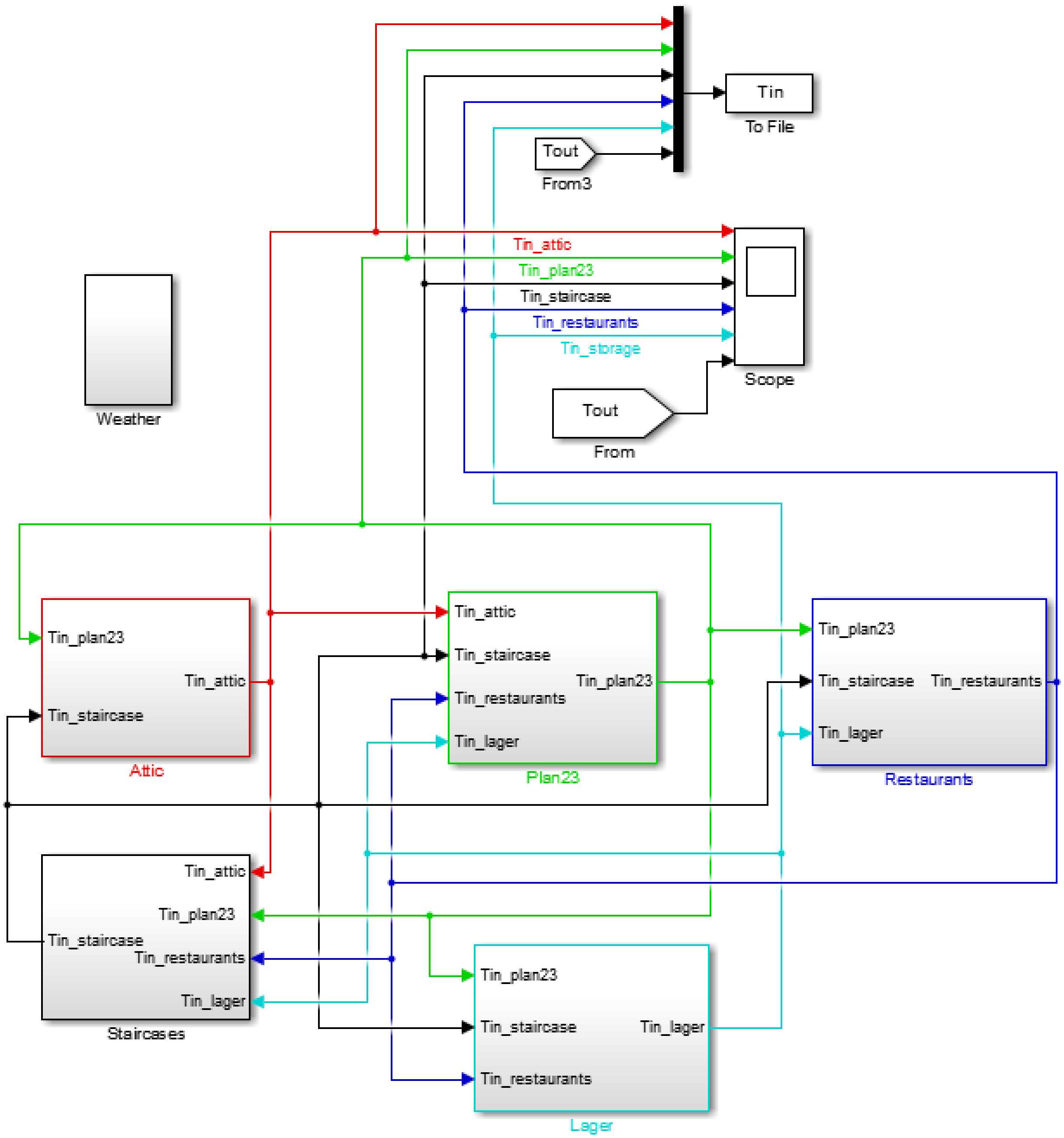

Figure B.1: All temperature zones of the building.

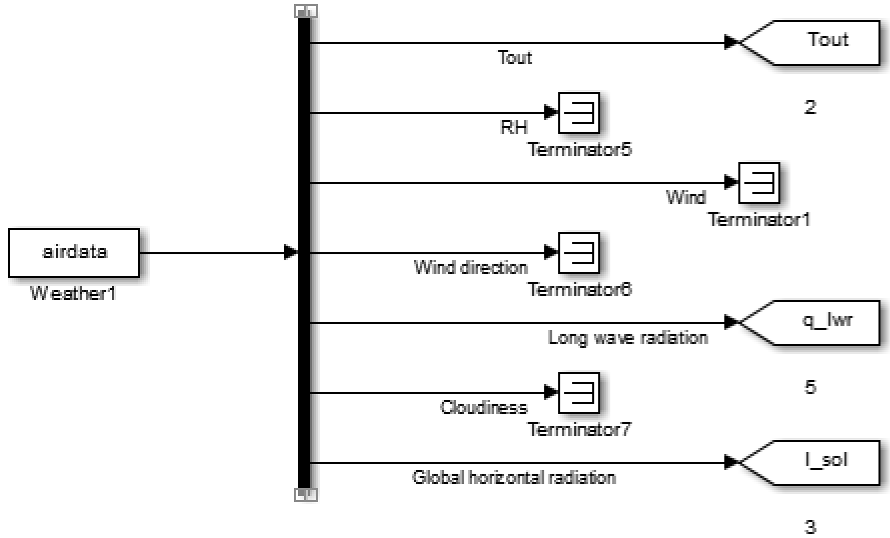

Figure B.2: Insertion of weather data.

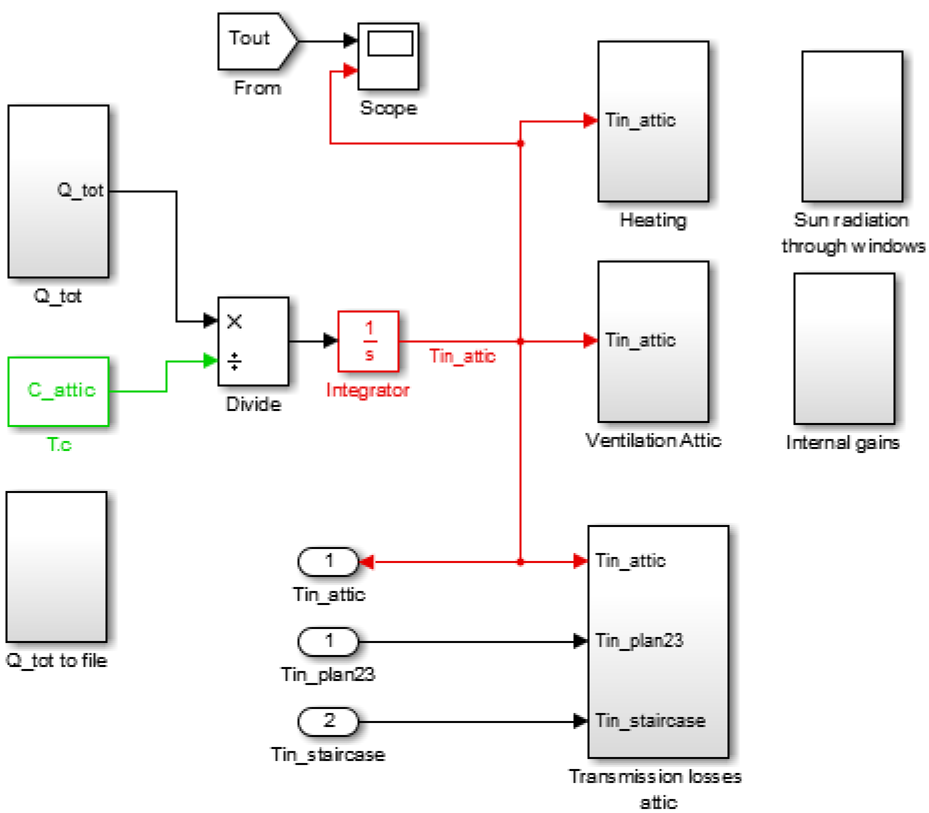

Figure B.3: The attic temperature zone.

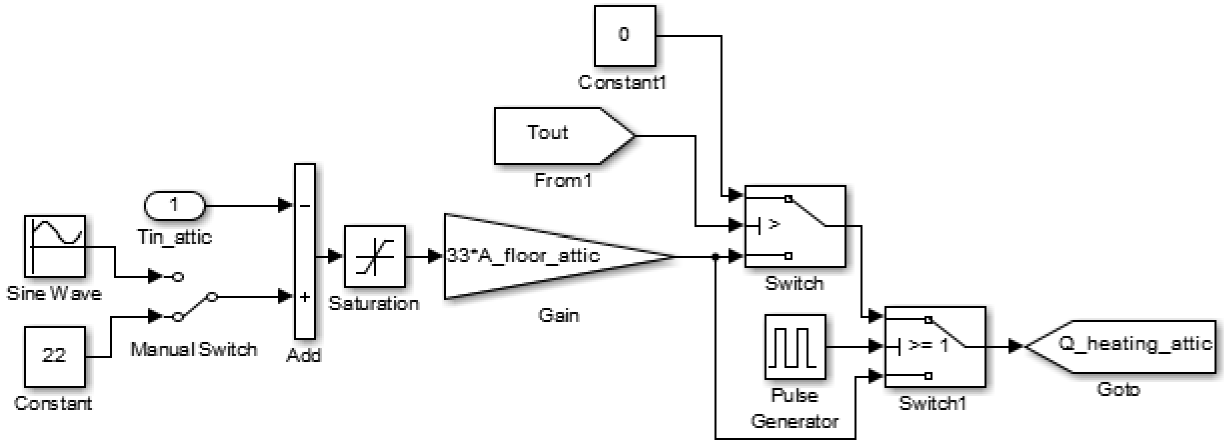

Figure B.4: The modelled heating system.

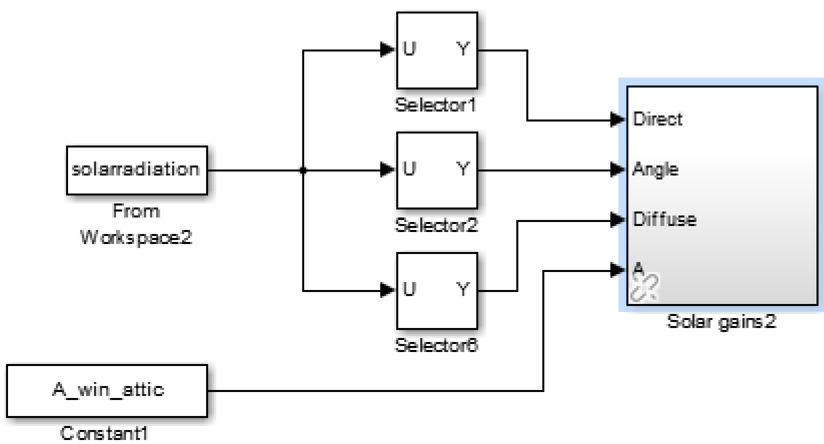

Figure B.5: Insertion of window data.

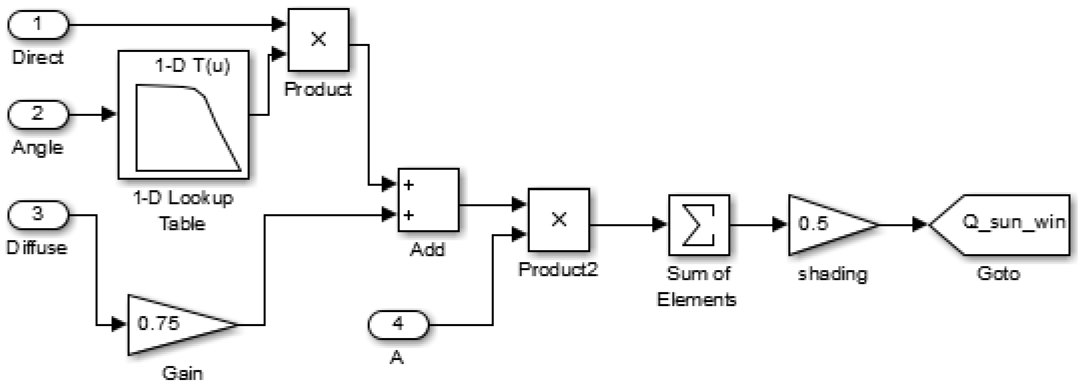

Figure B.6: Gains from solar radiation through windows.

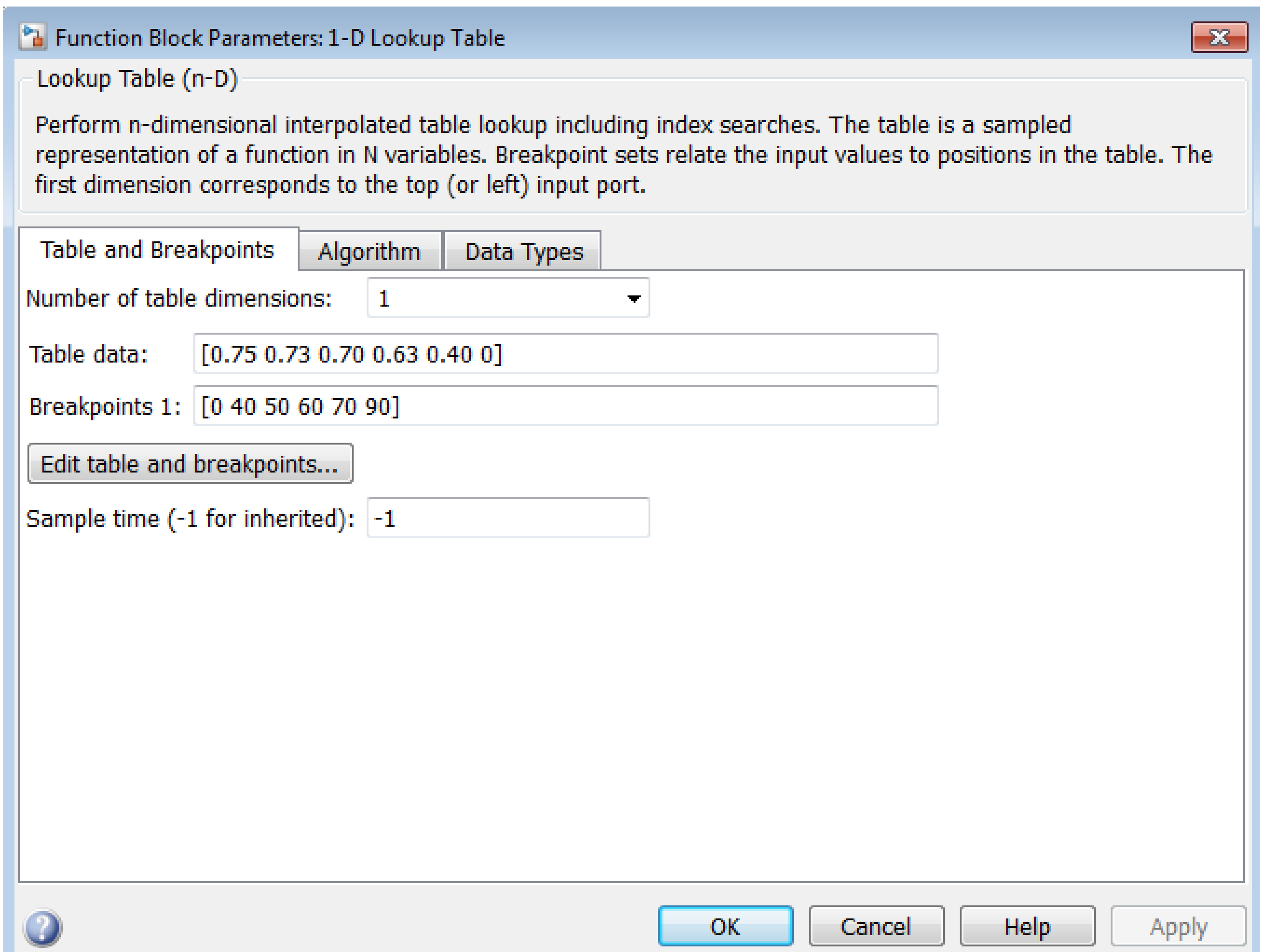

Figure B.7: Transmittance of direct solar radiation dependent on angle of incidence.

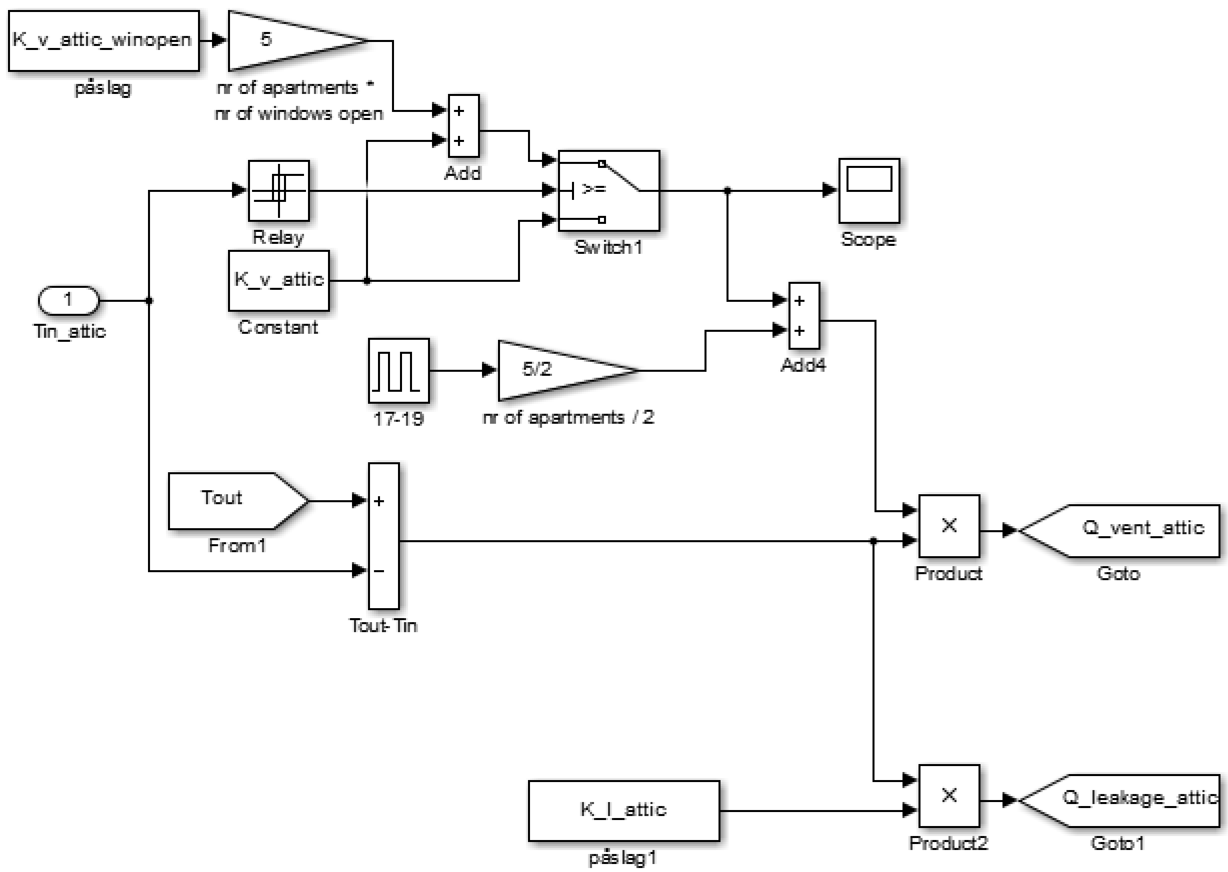

Figure B.8: Losses from ventilation and air leakages.

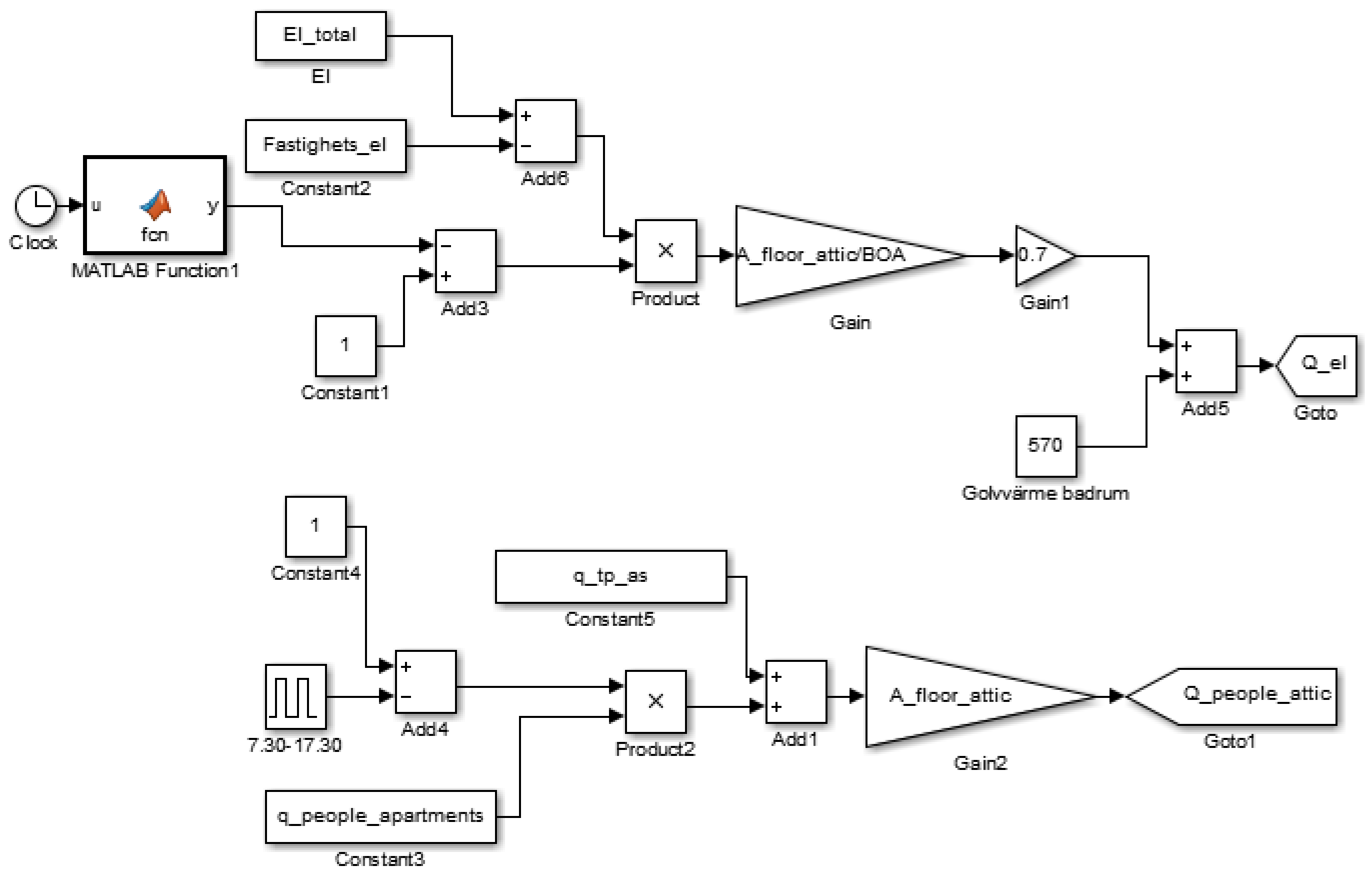

Figure B.9: Internal gains from electricity and people.

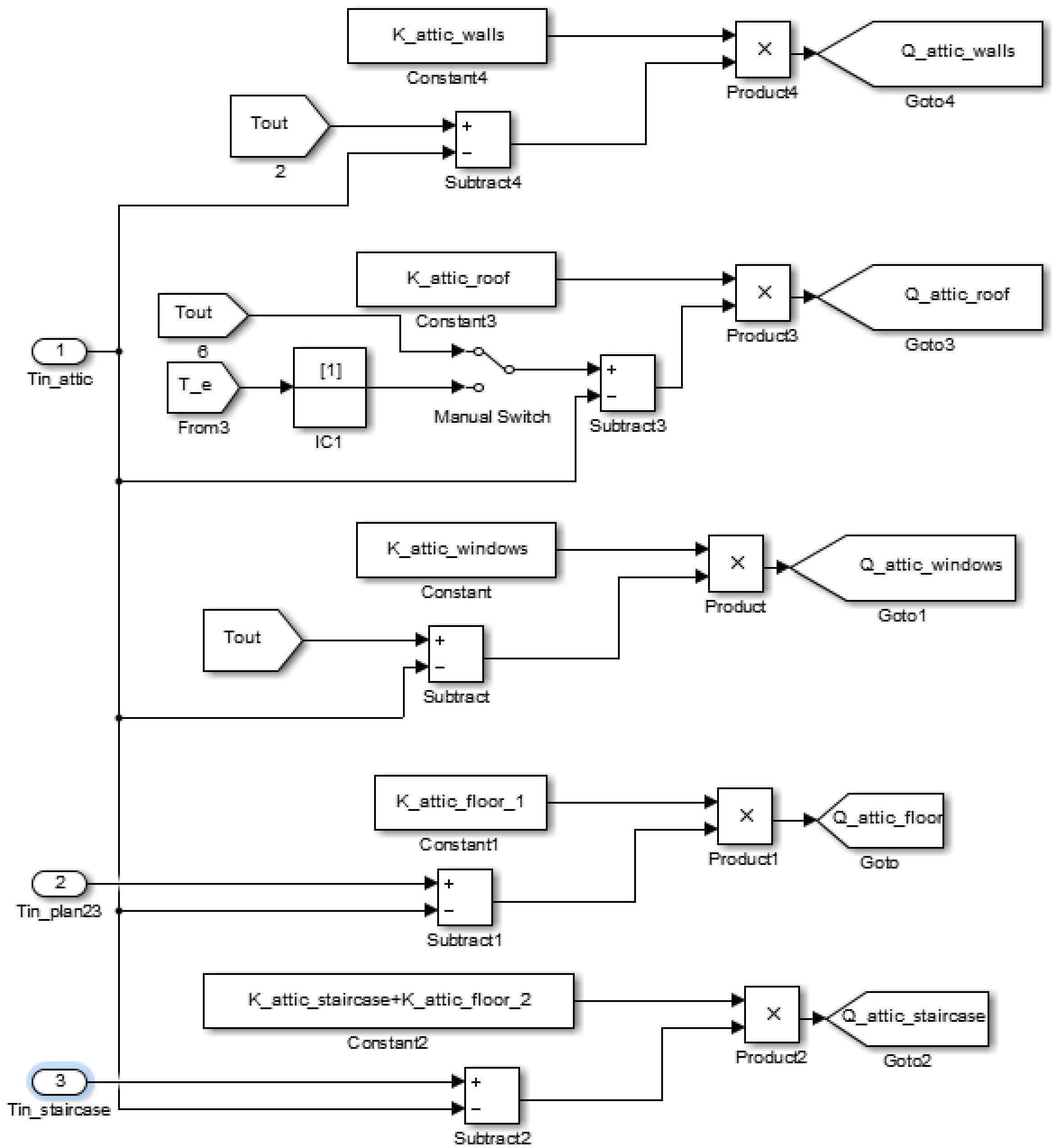

Figure B.10: Transmission losses.

C Input data for the temperature zones

Appendix C shows input parameters (except internal gains, which can be found in Section 4.2) for the different temperature zones.

Staircases

Transmission	*Area [m²]*	*U-value [W/(k m²)]*	*Thermal bridge*	*K-vlaue [W/K]*	Comment
Floor	42,3	0,574		24	
Inner wall - plan 23	292,6	0,248	20%	87	
Inner wall - restaurants	52,8	0,248		13	
Inner wall - storage	49,6	3,500		174	
Inner wall - attic	23,0	0,248	20%	7	
Ceiling - attic	32,8	0,143		5	
Facade - brick	40,8	1,400		57	
Facade - 50mm	67,0	0,419		28	
Windows (2-glass)	16,0	2,500		40	
Roof	9,5	0,170		2	
Ventilation		*Air flow [m³/s]*		*K-vlaue [W/K]*	
Exhaust air		0,017		20	
Airing		0,042		50	per window
Leakage	*Envelope area [m²]*	*Air flow [m³/s]*		*K-vlaue [W/K]*	
	138,8	0,008		10	
Heat capacity				C [J/K]	
Total				9,37E+06	
Direction windows	*Area [m²]*				
S					
N	6,4				
E					
SW	9,6				
NE					

Attic apartments

Transmission	*Area [m²]*	*U-value [W/(k m²)]*	*Thermal bridge*	*K-vlaue [W/K]*	*Comment*
Floor	370,2	0,143		48	
Floor - staircase	32,8	0,143		5	
Inner wall - staircase	23,0	0,248	20%	7	
Facade	195,5	0,170	20%	40	
Windows (3-glass)	42,0	1,100		46	
Roof	407,4	0,170	30%	90	
Ventilation		*Air flow [m³/s]*		*K-vlaue [W/K]*	
Exhaust air		0,148		178	
Airing		0,042		50	per window
Kitchen fans		0,063		75	between 17:00 - 19:00
Leakage	*Envelope area [m²]*	*Air flow [m³/s]*		*K-vlaue [W/K]*	
	644,9	0,039		46	
Heat capacity				C [J/K]	
Total				4,21E+07	
Direction windows	*Area [m²]*				
S	8,1				
N	11,2				
E	1,2				
SW	13,5				
NE	8,1				

Plan23

Transmission	*Area [m²]*	*U-value [W/(k m²)]*	*Thermal bridge*	*K-vlaue [W/K]*	*Comment*
Floor - restaurants	243,0	0,404		98	
Floor - storage	166,7	0,404		67	
Inner wall - staircase	292,6	0,248	20%	87	
Ceiling - attic	409,7	0,143		59	
Facade - 100mm	379,1	0,261	15%	114	
Facade - 50mm	316,8	0,419	15%	153	
Windows (3-glass)	128,9	1,100		142	
Windows (2-glass)	32,0	2,500		80	
Ventilation		*Air flow [m³/s]*		*K-vlaue [W/K]*	
Exhaust air		0,328		393	
Airing		0,042		50	per window
Kitchen fans		0,200		240	between 17:00 - 19:00
Leakage	*Envelope area [m²]*	*Air flow [m³/s]*		*K-vlaue [W/K]*	
	856,8	0,051		62	
Heat capacity				*C [J/K]*	
Total				7,65E+07	
Direction windows	*Area [m²]*				
S	54,7				
N	16,0				
E	11,7				
SW	16,0				
NE	62,5				

Restaurants

Transmission	*Area [m²]*	*U-value [W/(k m²)]*	*Thermal bridge*	*K-vlaue [W/K]*	*Comment*
Floor - ground	180,0	0,574		103	
Floor - basement	63,0	0,404	25%	32	
Inner wall - staircase	52,8	1,493		79	
Inner wall - storage	70,7	1,493		106	
Ceiling - plan23	243,0	0,404		98	
Facade - brick	140,8	1,493		210	
Windows (1-glass)	68,2	5,484		369	
Ventilation		*Air flow [m³/s]*		*K-vlaue [W/K]*	
Exhaust air		See table 4.1		See table 4.1	
Leakage	*Envelope area [m²]*	*Air flow [m³/s]*		*K-vlaue [W/K]*	
	598,0	0,036		43	
Heat capacity				*C [J/K]*	
Total				2,40E+07	
Direction windows	*Area [m²]*				
S	39,9				
N	1,6				
E	13,2				
SW	0,0				
NE	13,5				

Storage area

Transmission	*Area [m²]*	*U-value [W/(k m²)]*	*Thermal bridge*	*K-vlaue [W/K]*	*Comment*
Floor - ground	139,7	0,574		80	
Floor - basement	32,0	0,404	20%	16	
Inner wall - staircase	70,7	1,493		106	
Inner wall - restaurants	20,7	2,500		52	
Ceiling - plan23	171,7	0,404		69	
Facade - brick	218,7	1,493		326	
Windows (2-glass)	20,7	2,500		52	
Ventilation		*Air flow [m³/s]*		*K-vlaue [W/K]*	
Exhaust air		0,069		82	
Leakage	*Envelope area [m²]*	*Air flow [m³/s]*		*K-vlaue [W/K]*	
	379,1	0,023		27	
Heat capacity				*C [J/K]*	
Total				4,68E+07	
Direction windows	*Area [m²]*				
S	0,0				
N	3,3				
E	0,0				
SW	5,9				
NE	11,6				