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Modelling and assessment of energy performance with IDA ICE for a 1960's Mid-Sweden multi-family apartment block house

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Abstract

The present thesis has been carried out during the spring of 2017 on behalf of Gavlegårdarna AB. This is a public housing company in Gävle (Sweden) which is a large energy consumer, over 200 million SEK per year, and has the ambitious goal of reduce its energy consumption by 20 % between 2009 and 2020. Many multi-family apartment blocks were built during the "million programme" in the 60’s and 70’s when thermal comfort was the priority and not the energy saving. Nevertheless, this perspective has changed and old buildings from that time have been retrofitted lately, but there are many left still. In fact, one of these buildings will be retrofitted in the near future so a valid model is needed to study the energy saving measures to be taken. The aim of this thesis is to get through a calibration process to obtain a reliable and valid model in the building simulation program IDA ICE 4.7.1. Once this has been achieved it will be possible to carry out the building’s energy performance assessment. IDA ICE has shown some limitations in terms of thermal bridges which has accounted for almost 15 % of total transmission heat losses. For this reason, it is important to make a detailed evaluation of certain joints between elements for which heat losses are abundant. COMSOL Multiphysics® finite element software has been used to calculate these transmittances and then use them as input to IDA ICE to carry out the simulation.

Through an evidence-based methodology, although with some sources of uncertainty, such as, occupants’ behaviour and air infiltration, a valid model has been obtained getting almost the same energy use for space heating than actual consumption with an error of 4% (Once the standard value of 4 kWh/m2 for the estimation of energy use in apartments' airing has been added). The following two values have been introduced to IDA ICE: household electricity and the energy required for heating the measured volume of tap water from 5 °C to 55 °C. Assuming a 16 % of heat losses in the domestic hot water circuit, which means that part of the heat coming from hot water heats up the building. This results in a lower energy supply for heating than the demanded value from IDA ICE. Main heat losses have been through transmission and infiltration or openings. Windows account 11.4 % of the building's envelope, thus the losses through the windows has supposed more than 50 % of the total transmission losses. Regarding thermal comfort, the simulation shows an average Predicted Percentage of Dissatisfied (PPD) of 12 % in the worst apartment. However, the actual value could be considerably lower since the act of airing the apartments has not been taken into account in the simulation as well as the strong sun's irradiation in summer which can be avoided by windows shading. So, it could be considered an acceptable level of discomfort. To meet the National Board of Housing Building and Planning, (Boverket) requirements for new or rehabilitated buildings, several measures should be taken to improve the average thermal transmittance and reduce the specific energy use. Among the energy saving measures it might be interesting replace the windows to 3 pane glazing, improve the ventilation system to heat recovery unit, seal the joints and intersections where thermal bridges might be or add more insulation in the building’s envelope.

Keywords: retrofit, building’s energy performance, simulation, modelling, heat transfer, thermal bridge, IDA ICE, COMSOL.

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Contents

Glossary

A_{temp} — The area enclosed by the inside of the building envelope of all storeys including cellars and attics for temperature-controlled spaces are intended to be heated to more than 10 °C. The area occupied by interior walls, openings for stairs, shafts, etc., are included. The area for garages, within residential buildings or other building premises other than garages, are not included.

The building's energy use — The energy which, in normal use during a reference year, needs to be supplied to a building (often referred to as "purchased energy") for heating (Euppv), comfort cooling (Ekyl), hot tap water (Etvv) and the building's property energy (Ef). If underfloor heating, towel dryers or other devices for heating are installed, their energy use is also included. The building's energy use is calculated using the equation below,

$$E_{bea} = E_{uppv} + E_{kyl} + E_{tvv} + E_{f}$$

The building's property energy — The part of the building electricity consumption that is related to the building's needs, where the electricity consuming appliance is located in, under or affixed to the exterior of the building. This includes permanently installed lighting of common spaces and utility rooms. It also includes energy used in heating cables, pumps, fans, motors, control and monitoring equipment and the like. Externally locally placed devices that supply the building, such as pumps and fans for free cooling, are also included. Appliances intended for use other than for the building, such as engine and compartment heaters for vehicles, battery chargers for external users, lighting in gardens and walkways, are not included.

The building's specific energy use — The building's energy use divided by *A*temp expressed in kWh/m^2 and year. Domestic energy is not included. Neither is occupancy operational energy used in addition to the building's occupancy basic operation adapted requirements for heat, hot water and ventilation. The building's specific energy use (*E*beaspec) is calculated using the equation below,

$$E_{\text{beaspec}} = E_{\text{bea}} / A_{\text{temp}}$$

Average thermal transmittance U_m

The average thermal transmittance for structural elements and thermal bridges (W/m^{2}K) as determined by SS-EN ISO 13789:2007 and SS 24230 (2) and calculated using the formula below,

$$U_m = \frac{(\sum_{i=1}^{n} U_i A_i + \sum_{k=1}^{m} l_k \Psi_k + \sum_{j=1}^{p} X_j)}{A_{om}}$$

where U_i — Thermal transmittance for structural elements in (W/m^{2}K).

A_i — The surface area of the structural element i in contact with heated indoor air (m^2). For windows, doors, gates and the like, *A*i is calculated using the external frame dimensions.

Ψ_k — Thermal transmittance for the linear thermal bridge k (W/mK).

l_k — The length in relation to the heated indoor air of the linear thermal bridge k (m).

X_j — Thermal transmittance for the point shaped thermal bridge j (W/K).

A_{om} — Total surface area of the building envelope facing the heated indoor air (m^2). The building envelope refers to those structural elements that separate heated parts of dwellings or non-residential premises from the outside, the ground or partially heated spaces.

All this definitions have been extracted from Boverket´s building regulations – mandatory provisions and general recommendations, BBR.

Predicted mean vote (PMV)	PMV an index that predicts the mean value of the votes of a large group of persons on the seven-point thermal sensation scale. The ASHRAE thermal sensation scale, which was developed for use in quantifying people's thermal sensation, is defined as follows: +3 hot +2 warm +1 slightly warm 0 neutral –1 slightly cool –2 cool –3 cold
Predicted percentage of dissatisfied (PPD)	PPD is an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people determined from PMV.
Thermal comfort	That condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation.
Operative temperature (To)	The uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment.

All this definitions have been extracted from ASHRAE Standard 55-2010

List of Figures

List of Tables

1 Introduction

1.1 Background

Old buildings were built with the target of obtaining thermal comfort but without much concern about how much energy could cost it. However, since the 70's oil crisis the attention towards this topic has increased drastically in Europe, when the member states realized about the issue of natural resources limitation and pollutants emission. The energy consumption is increasing continuously and a noteworthy share belongs to buildings, so that is why the retrofitting is gaining importance for the improvement of their energy efficiency. Retrofitting of buildings plays a key role in energy savings and emission reduction for countries with stabilised building stocks. As in every improvement process the aim is to find cost-effective and technically better options for the building [1]. According to the IEA residential energy consumption will grow at rate of 9.1% to 2030, therefore some energy efficiency measurement must be taken in order to reduce that value [2].

1.1.1 Energy use in Europe and Sweden

Climate change mitigation and energy security it is a current issue for all the EU member states. In fact, Sweden is the third European country consuming most primary energy per capita [3] and the awareness of the critical situation has made a higher change in attitude towards sustainability, green buildings and renewable energies comparing to other EU countries.

In the chart below it is visible that Luxembourg is the major consuming country per capita, followed by Finland and then Sweden. The values are measured by kgoe (kilograms of oil equivalent).

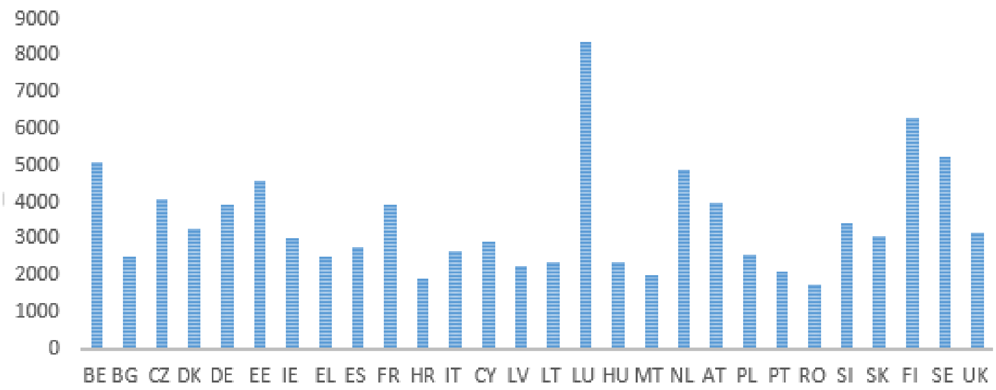

Figure 1.1: Final energy consumption per capita by country in 2012 (Europe)[1]

[1] Final energy consumption per capita /www.ec.europe.eu

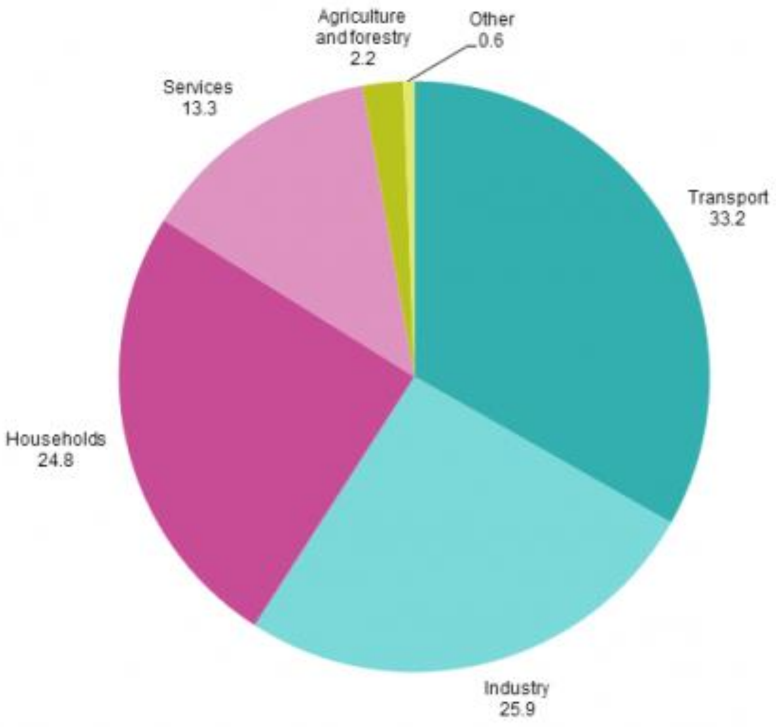

Figure 1.2: Final energy consumption (%), EU-28, 2014[2]

Household activities accounted for almost 25% of final energy consumption in 2014 [4]. This implies a large part that cannot be ignored and for this reason some regulations have been set that will be mentioned later.

1.1.2 Energy policy and targets

European Union has five headline targets by 2020 and one of them is energy related, known as 20-20-20 energy and climate targets. There are three main objectives: to reduce in a 20% greenhouse emissions comparing to the 1990's levels, to rise the usage of renewable energy sources in final energy use to a share of 20% and to enhance the energy systems by increasing energy efficiency by 20%[5].

EU has also set up national targets for each member country. In the case of Sweden are pretty ambitious and eco-friendly. While Europe is up to fight for the RES target of 20%, Sweden was compromised to increase this value to 49% by 2020 [4]. Indeed this national target was achieved by 2012 with 51 % share of renewables in energy in gross energy consumption [6]. Moreover, greenhouse emissions should be 40% lower by 2020 compared with 1990 levels. One of the most ambitious Swedish national goals, is to have an energy supply with zero net emissions by 2050 [2] as well as the reduction of energy demand in 50 % by 2050.

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[2] Final energy consumption, EU.28, 2014, Eurostat/www.ec.europa.eu

1.1.3 Energy in buildings

In order to understand building situation in Sweden, some indicators can be helpful. According to Swedish Energy Agency, in 2014 when the last statistics were provided, residential and services accounted 38% of the total energy use of the country [7]. It has decreased about 6% since 1970, due to the continuous energy efficiency measures taken in the sector. However, every year the life standard is growing so the domestic electricity consumption as well, from 9.2 TWh to 21.5 TWh in the same time period [7].

Residential sector accounts 21% of the total energy demand. From this percentage 70% belongs to the space heating, 10% is for hot water and the other 20% belongs to electricity [8].

The vast energy consumption in buildings is becoming a worldwide issue and the awareness is increasing in the society. Therefore, International Energy Agency has stablished some building regulations. In fact, Energy Performance of Buildings Directive (EPBD) has taken action on this matter and with the help of the Energy Performance Declaration (EPC) more information related to the energy efficiency of the buildings can be provide [9]. EPBD and EPC are defined as:

> "*The Energy Performance of Buildings Directive (EPBD, Directive 2010/31/EU) aims to steer the building sector towards ambitious energy efficiency standards and increased use of renewable energy sources.*[3] *"*
>
> *"The Energy Performance Certificate (EPC) plays a key role in this process, as it informs potential tenants and buyers about the energy performance of a building unit (e.g., an apartment or office) or of an entire building, and allows for comparison of buildings and building units in terms of energy efficiency.*[4] *"*

<u>BBR</u>

Boverket (National Board of Housing Building and Planning) is the responsible for the Swedish building regulation BBR. It contains several rules and guidelines about the overall aspects of the building, such as, energy management, safety and designing among others. In the case of the energy conservation there is a variation in climate throughout the country, for this reason Sweden is divided into four climate zones depending on the latitude. The studied building is located in Gävle, hence it belongs to climate zone 2.

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[3] Energy Performance of Buildings Directive 2016 (EPBD)/www.epbd-ca.eu
[4] Energy Performance of Buildings Directive 2016 (EPBD)/www.epbd-ca.eu

Table 1: Climate zones in Sweden[5]

Climate Zone

Climate Zone	
1.	Norrbottens, Västerbottens och Jämtlands län.
2.	Västernorrlands, Gävleborgs, Dalarnas och Värmlands län
3.	Jönköpings, Kronobergs, Östergötlands, Södermanlands, Örebro, Västmanlands, Stockholms, Uppsala, Gotlands och Västra Götalands län utom Härryda, Mölndal, Partille och Öckerö kommun.
4.	Kalmar, Skåne, Hallands och Blekinge län Samt Härryda, Mölndal, Partille och Öckerö kommun.

According to BBR new or retrofitted buildings must ensure the building's specific energy use and the average thermal transmittance, depending on the heating system, as it follows:

Table 2: Regulation for buildings with non-electrical heating and buildings with electrical heating[6]

Multi-dwelling buildings (non-electrical heating)	Climate zone 1	Climate zone 2	Climate zone 3	Climate zone 4
The building's specific energy use ($kWh/m^2/year$)	115	100	80	75
Average thermal transmittance (W/m^2K)	0.4	0.4	0.4	0.4

Multi-dwelling buildings (With electrical heating)	Climate zone 1	Climate zone 2	Climate zone 3	Climate zone 4
The building's specific energy use ($kWh/m^2/year$)	85	65	50	45
Average thermal transmittance (W/m^2K)	0.4	0.4	0.4	0.4

[5] Boverket-byggregler/klimatzoner/www.rockwool.se
[6] BBR 2015/ www.boverket.se

OVK (Obligatory Ventilation Control)

The compulsory ventilation control in all buildings has been a requirement since 1991. Every multi-family house owner is responsible to ensure OVK is carried out by a certified inspector periodically. The aim is to guarantee a comfortable and appropriate indoor climate regarding to the ventilation system. Through OVK the following information must be provided[7]:

- ✓ There is no pollutants in the ventilation systems that can enter and spread in the building.
- ✓ Maintenance guidelines and instructions easy available
- ✓ Ventilation system is running and working as it should be
- ✓ Energy saving measures for ventilation maintaining indoor environment

1.1.4 The Million programme

During the first decades of the post-war era the need for new housing was pretty large and growing quickly. In Sweden, fast urbanization and the rise in prosperity as well as demands for higher housing standards, led to years-long housing queues. For this reason the Swedish parliament decided to carry out a project in which one million houses would be built between the years 1964-1975. Many of the buildings of this era have been maintained quite well due to the correct maintenance of them, however some multi-family buildings have had to undergo certain retrofitting measures.

During the Million Programme also known as "the record years" a huge amount of residential buildings were built massively and with similar architecture. Most of them were had concrete as building material and a quite low insulation [10]. In fact, the general thought about this years for many people is a large-scale housing buildings made of grey pre-cast concrete slabs [11]. However, it was a wide range in those home designs where only 15-20 % of the multi-family apartments were built by pre-cast concrete. Besides, regarding to the façade materials, brick and cement rendering were the most used ones, followed by concrete panels.

Further, 66 % of the Million Programme's buildings were multi-family apartments and 50 % of them were constructed in neighbourhoods surrounded by the same kind of buildings which belong to the same owner[11]. The concern of green areas nearby homes, came up with the urban planning of "houses in a park" which it was carried out in Sätra (neighbourhood in north of Gävle where the studied building is located) also known as "the white city"[11].

[7] BBR 2015/ www.boverket.se

1.2 Literature review

The present thesis is based on a Building Energy Performance Simulation (BEPS) tool which compares measured data with the output results from the simulation. Throughout this procedure of reconciling process, called calibration, more reliable and accurate results can be obtained. It is important to understand what is a building energy simulation and how can it be classified. Scientific models can be Diagnostic or Prognostic on one hand and Law-Driven or Data-Driven on the other. Building Energy Simulation (BES) models, belong to prognostic law-driven type [12]. They are used for predicting the behaviour of a system according to defined laws, such as, heat transfer and energy balance. However, the inverse methods used for energy use estimation in buildings can be also be categorized in three approaches, detailed model calibration among them. This is the most accurate and detailed approach for predicting the performance of a building, where a law-driven model is used and the input data are tuned in order to match the measured data which is quite used for retrofit analysis [12].

On the other hand there are also some issues related to BEPS (Building Energy Performance Simulation) calibration. One of the most highlighting issue is the uncertainty, depending on the source they can be distinguished four different types; specification, modelling, numerical and scenario uncertainty. Keeping on with the uncertainties, climate is a vital boundary condition for building simulations which can affect in buildings' energy performance [1]. Normalized climate data which is usually used in simulation programs, is not exactly the same as the actual climate a studied year. This can result in some deviations from measured energy use and indoor temperatures.

There are several discrepancies between the actual data and the simulated results. Occupants' behaviour is relevant when doing an energy simulation of a building, this is one of the external factors, which are inputs in the simulation program, affecting the results. It is important to ask to the occupants how often do they open windows, change the thermostat or try to avoid the direct solar radiation. All this information is helpful when designing a model of the building. The difference, as mentioned before, is known as "performance gap" which mainly can be related to estimating wrong U-values and occupants' behaviour, ventilation and air infiltration among others [13].

The residents can be asked by a questionnaire about the estimation of their energy use in electrical devices with a choice between passive, medium or active [13]. Building simulations' input can be tuned depending on the answer of the occupants. Moreover, it is important data on the number of the residents living in the building in regular day. According to this results, an occupancy profile can be made.

Another aspect to take into account is the surrounding buildings. In the actual conditions, normally there are other buildings around. This should not be ignored either, because can be affecting the solar radiation into the studied building. Therefore, they can be simulated as shading objects, in order to simulate the outdoor conditions.

For determining the indoor thermal conditions and meet the measured data, as far as possible, the outdoor conditions and buildings' characteristics have a major relevance. Heat transmission from outdoor to indoor or the other way round, depends on the difference on the temperature between the two sides. Through heating and cooling the indoor temperature varies, so the transmission does as well. Solar energy transmission into the building also depends, on the occupants’ behaviour when using curtains, blinds or anything to avoid the sunlight. Infiltration through holes, doors and windows is considerably influential in the indoor climate [13].

One of the most noteworthy facts when studying the energy performance of a building is the transmission losses through the envelope. Therefore, insulation of the buildings has become the spotlight in Sweden. In fact, when more insulation is used the relative impact of the thermal bridges increases and for this reason is essential to focus on the proper calculation of the transmission heat transfer and not misjudge the potential of the thermal bridges [14]. Actually there are different methods for carrying out this process and it is interesting to point out that according to a case study depending on the measuring method the share of thermal bridges varies but not the overall heat transfer coefficient of the envelope [14]. Indeed, according to Bovekert, thermal bridges normally account between 15-20% of the over-all transmission losses [15].

Once a building is constructed, as the years go by, moisture in building might be a problem that damages the envelope and the performance of the building. The undercooling phenomenon, means an external condensation on facades which can also be simulated [16]. Internal heat sources are another significant variable for the energy simulation process. This variables changes with the internal generation that has to be assumed. Depending on the activity level of the people inside the building, the internal generation can be higher or lower. In a case study of Swedish dwellings [17] the following values where supposed. 85 W/person in when the occupants were in their bedrooms, 150 W/person if they were eating in the kitchen and 135 W/person of heat generation in the living room. On the other hand, regarding to the lights it was presumed they were turned on when the area was occupied. Equipment of the kitchen full-time running and living rooms one half-time.

For the evaluation of the thermal comfort of the residents, Predicted Mean Value (PMV) and Predicted Percentage Dissatisfied (PPD) are appropriate tools. Parameters like mean radiant temperature and operative temperature are also regulated by the ISO 7730[8]. For the PPD the standard value is 15% [17] although according to ASHRAE a PPD < 10% would be the acceptable value for thermal comfort [18].

[8] EN-ISO 7730, Ergonomics of the thermal environment

1.3 The studied building

The multi-family apartment block studied is located in Sätra, north of Gävle. The building was built during the “Million Program” in 1966 and it has never been retrofitted since then. The building is composed of four floors; the basement with storage rooms and laundry room, and the ground level, first and second floors containing apartments. The building comprises 34 apartments of different sizes. The block could approach a rectangular shape in which the longer facades are oriented to the east and west.

Figure 1.3: Gråstensvägen 23-29

There is no cooling system and all the heating comes from the district heating system. Regarding to HVAC (Heating Ventilation and Air Conditioning) system, local mechanical exhaust ventilation systems which can be regulated by the occupants from the kitchen. In the district heating controlling room, there is a 2-step heat exchanger system, one for tap water and the other for heating system.

The actual household electricity consumption of the whole block in 2016 was 80 419 kWh and the district heating consumption for the same period 366.4 MWh where 1746 m^3 of hot water were heated. According to the chart of the mean indoor temperature of the block throughout this year the set point might be at 21 °C during the heating season since the lowest value registered is at that temperature.

1.4 Aims

The purpose of this thesis is to create a validated model by tuning parameters of IDA ICE building energy simulation program, for the future retrofitting process of a multi-family apartment block on behalf of Gavlegårdarna. The objective is to get the energy used for space heating as close as possible to the measured data. The input data for IDA ICE will be household electricity and the energy required for heating up the measured supplied tap water from 5 °C to 55 °C. Therefore the value to compare is the energy consumed in space heating where it can be shown how well the model of the building has been designed through the simulation program. Finally, once the results have been obtained building's energy performance assessment will be carried out.

2 Theory

2.1 Heat transfer

Heat transfer is the science that studies the energy transfer between material bodies due to a temperature difference. In order to reach the thermal equilibrium the heat is transferred from the high-temperature region to the low-temperature region. The study of heat transfer is fundamental when determining the design of a building. For the design of active and passive systems which deliver the required thermal comfort conditions heat losses are the key. The aim is always to minimize the energy consumption of the entire building. For an energy-efficiency building located in a cold climate, transmission losses through the envelope are the reason for a large part of the heating demand [14].

Heat transfer complements the first and second laws o thermodynamics and is used to predict the energy transfer rates under certain specific conditions.

Regarding to the first law, energy cannot be created or destroyed, but converted from one energy form to another. In this case, there is not any work involved, therefore the heat transfer is related to the internal energy of the system.

$$\Delta U = Q - W \quad [J] \tag{1}$$

Where ΔU = internal energy of a system [J]

Q = heat added to the system [J]

W = work done by the system [J]

Heat transfer can be divided in three types: conduction, convection and radiation:

2.1.1 Conduction

Conduction heat transfer occurs between solids or stationary fluids due to inter-molecular interactions as a result of a temperature difference. Through Fourier's Law conductive heat transfer can be determined:

$$\dot{q} = -k\,A\,\frac{dT}{dx} \tag{2}$$

Where $\dot{q}$ = heat-transfer rate [W]

A = heat transferring area [m^2]

k = thermal conductivity of the material [W/m K]

$\frac{dT}{dx}$ = temperature gradient in the direction of heat flow [K/m]

Thermal conductivity is a thermodynamic property of the material and constant value. The bigger the k value is the better heat conductor is it. The thermal resistance is how well a material layer transfers heat by conduction and depends on the thermal conductivity and the thickness of the layer where the heat flows. These two terms are related in the following manner.

$$R = \frac{l}{k} \tag{3}$$

Where R = conductive thermal resistance [m^2K/W]

l = thickness of the layer [m]

k = thermal conductivity of the material [W/m K]

Materials with high thermal resistance are good insulators.

Regarding to the conduction in buildings, this heat transfer mechanism must be studied carefully because it can influence significantly in the loss of cooling during the summer or heating on winter period. This might result in large operating costs, as well as thermal discomfort for the occupants and higher emissions to the atmosphere.

2.1.2 Convection

The convective heat transfer occurs when a fluid is in contact with a solid body which has higher or lower temperature than the surroundings or it can also happen between two fluids. If there is no outside influence and the movement of the media depends only on the density variation driven by buoyancy forces, natural convection takes place. However, if there is forced convection, then fluid is forced by an external influence and the movements depend on outside factors.

Newton's law of cooling is the equation used to express the overall effect of convection:

$$\dot{Q} = h_c\, A\, (T_w - T_\propto) \tag{4}$$

Where $\dot{Q}$ = heat-transfer rate [W]

A = heat transferring area [m^2]

h_c = convective heat transfer coefficient [W/m^2K]

T_w = temperature of the solid surface [K]

$T_\propto$ = temperature of the fluid [K]

Convection heat transfer has dependence on many factors, such as, the velocity of the fluid, surface geometry and properties and viscosity of the fluid and its thermal properties among others. In order to summarize convective heat-transfer coefficient is used, which might be calculated through experimental correlations. For forced convection Nusselt (Nu) dimensionless number can be used and for natural ventilation Grashof (Gr) number.

In this case the thermal resistance is directly the inverse to the convective heat transfer coefficient h_c:

$$R = \frac{1}{h_c} \tag{5}$$

Where R = convective thermal resistance [m^2K/W]

h_c = convective heat transfer coefficient [W/m^2K]

Air movement is necessary when designing a building, in order to reduce odours, moisture and condensation as well as to improve the thermal comfort of the occupants.

2.1.3 Radiation

All the bodies with a higher temperature than 0 K (-273.15 °C) emit thermal radiation and they also absorb the emitted radiation by the surrounding surface. The difference between the emission and absorption of radiation in a body results in a net heat transfer, which produces a change in the temperature of the body. In this case there is not material medium involved and the mechanism is the electromagnetic radiation.

In other terms, the total radiation energy leaving (emitted and reflected) from a body's surface it is called Radiosity, J [W/m^2] and the radiation energy that falls upon a surface is called Irradiation, G [W/m^2].

Blackbody is an ideal thermal radiator which absorbs all the flux reaches its surface and the energy emitted is stated by the Stefan-Boltzman:

$$\dot{q}_{emitted} = \sigma\, A\, T^4 \tag{6}$$

Where $\dot{q}_{emitted}$ = blackbody emitted radiation [W]

A = heat transferring area [m^2]

σ = Stefan-Boltzmann constant ≈5,699·10^{-8} [W/m^{2}K^4]

T= absolute temperature of the blackbody [K]

However, blackbodies (ε=1) does not exist in the reality, the emissivity is always below that value, which means that real surfaces do not emit nor absorb radiation as efficiently as a black body. Apart from that is important to take into account that not all the radiation emitted will reach the other surface, some of it is lost to the surroundings, for this reason the "view factor" must be added to the equation as well.

$$q_{12} = \varepsilon_1\, F_{12}\, \sigma\, A\, (T_1^4 - T_2^4) \tag{7}$$

$$q_{12} \approx A\, \varepsilon_1 \sigma\, (4T_m{}^3)\, (T_1 - T_2) \approx A\, h_r\, (T_1 - T_2) \tag{8}$$

Where q_{12} = radiant heat-transfer rate [W]

ε_1 = emissivity of the grey body

F_{12} = view factor, the fraction of the radiation which leaves the surface 1 and reaches the surface 2
A = heat transferring area [m^2]

hr = radiation heat transfer coefficient [W/m^{2}K]

T_1 = temperature of the surface 1 [K]

T_2 = temperature of the surface 2 [K]

T_m = mean temperature of T_1 and T_2 [K]

2.1.4 Surface thermal resistance

Surface thermal coefficient involves the heat transfer through convection and radiation. It means the total heat transfer per m^2 divided by the temperature difference between the surface and the fluid. Therefore the surface thermal resistance can be defined as it follows:

$$R_s = \frac{1}{h_c + h_r} \tag{9}$$

Where R_s = Surface resistance [m^{2}K/W]

h_c = conduction heat transfer coefficient [W/m^{2}K]

h_r = radiation heat transfer coefficient [W/m^{2}K]

2.1.5 U-value

By the temperature difference across a building construction thermal transmission coefficient or U-value quantifies the heat flow through it. This value depends on the sum of all thermal resistances of the materials and the surface resistances:

$$U = \frac{1}{R_{si} + \sum R + R_{se}} \tag{10}$$

Where the U-value means the heat flow per square meter of component per degree temperature differential across it [W/m^{2}K]. The smaller this value is, the better insulated is the construction.

R_{si} = indoor's surface resistance [m^2K/W]

R_{se} = outdoor's surface resistance [m^2K/W]

2.2 Transmission losses and thermal bridges

Due to the temperature difference between indoors and outdoors of a building, there is a heat transfer through the envelope of the building where transmission losses occurs. The indoor temperature is normally relatively constant, however the outdoor temperature varies significantly with the climate. In northern countries reaches negative values during the winter period, therefore is essential to try to minimize this value. The size of the transmission losses depend mainly on the outdoor temperature and the thermal insulation of the building.

To calculate the heat transmission the transmission heat transfer coefficient according to ISO 14683 is calculated by the following equation[9]:

$$H_D = \sum_i A_i\, U_i + \sum_k l_k\, \Psi_k + \sum_j X_j \qquad \text{[W/K]} \qquad (11)$$

Where A_i : Area of element *i* of the building envelope [m^2]

U_i : Thermal transmittance of the element *i* of the building envelope [W/m^2K]

l_k : Length of linear thermal bridge *k* [m]

Ψ_k : Linear thermal transmittance of linear thermal bridge *k* [W/mK]

X_j : Point thermal transmittance of the point thermal bridge *j* [W/K]

In the study case point thermal bridges have been neglected, however if they were relevant the calculation should be carried out in accordance with ISO 10211[10].

Thermal bridges exist in several structure junctions of the building envelope. For technical reasons sometimes a material with poor thermal insulation penetrates into a better insulating material and disturbs the effectiveness of insulation. Therefore there are extra heat losses in these particular sections.

The typical areas for thermal bridges are the junctions between external walls and internal walls, internal and external floors, balconies, roof and windows. Normally in Sweden, thermal bridges

[9] ISO 14683: 2007, Thermal bridges in building construction-Linear thermal transmittance – Simplified methods and default values.

[10] ISO 10211:2007, Thermal brides in building construction – Heat flows and surface temperatures- Detailed calculations.

can make up 15 to 20 % [15] of the total heat transfer losses. It's essential to pay special attention to these losses because they can cause thermal discomfort on the occupants and moisture problems in the building.

2.2.1 Ψ-value

For the calculation of Ψ-value computerized programs are needed for instance a finite element software. The method to follow is stated in ISO 10211:

1. Build a reference case without the thermal bridge and calculate the net heat flux ($\dot{Q}ref$), in 2-D (two dimensions, x and y- coordinates) the construction is 1 m in the z-direction.

2. Build the real construction with the thermal bridge and calculate the net heat flux ($\dot{Q}tot$)

3. Once the heat flows are obtained, Ψ can be calculated through the following equation:

$$\dot{Q}tot = \dot{Q}ref + \Psi \cdot 1 \cdot \Delta T \qquad \text{[W]} \qquad (12)$$

$$\Psi = \frac{\dot{Q}tot - \dot{Q}ref}{1 \cdot \Delta T} \qquad \text{[W/m K]} \qquad (13)$$

To facilitate the process it can be assumed the temperature difference between outdoor and indoor to be 1 K, it will not affect the result.

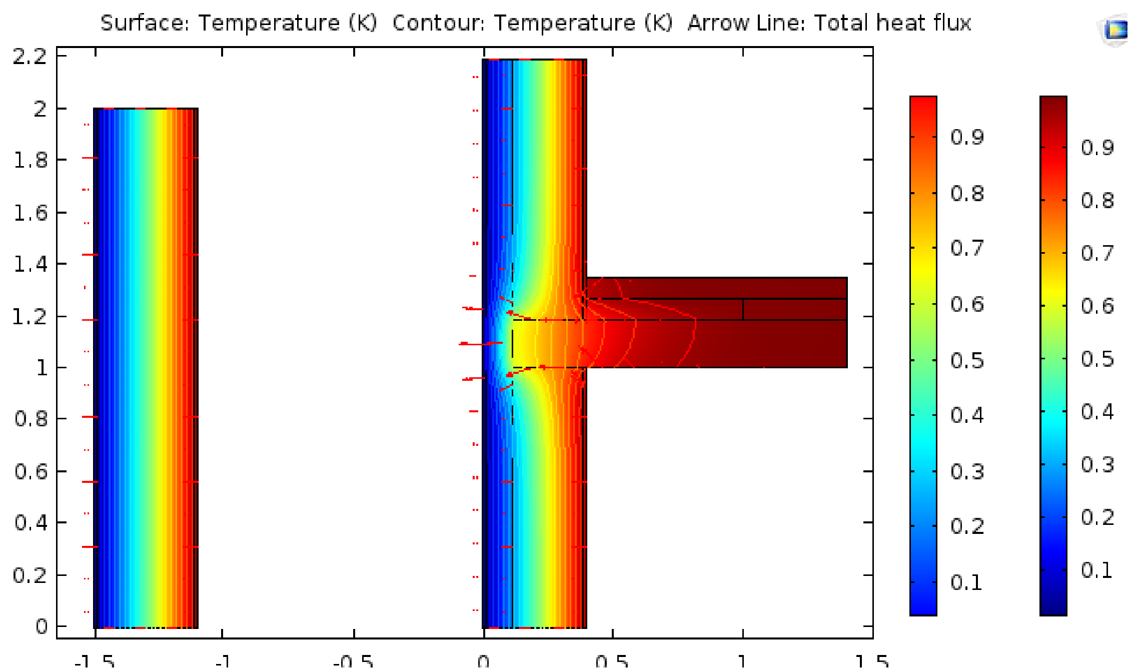

Figure 2.1: Example of a thermal bridge calculation between external wall and internal slab

Figure 2.1 belongs to one of the simulations carried out for this thesis. The rest of the thermal bridges are attached at Appendix A – COMSOL results

2.3 Ventilation

Ventilation is an air exchange in a closed area in order to have an acceptable air quality and comfort level. Air-flow can be measured both in absolute and specific units, such as in m^3/h per m^3 room volume. Specific air flow is usually called ACH which means *air change rate per hour.*

In every occupied zone ventilation is needed and the air-flow is determined by the requirements of the place, internal heat and pollutants generation and thermal climate. The most common indicator for a ventilation system can be the one for Specific Fan Power:

$$SFP = \frac{Electric\ power\ rating\ (kW) of\ supply\ air\ fan + rating\ (kW) of\ extract\ air\ fan}{supply\ air\ flow\ and\ extract\ air\ flow\ (\frac{m^3}{s})} \qquad (14)$$

This value is calculated by IDA ICE depending on the values introduced for the ventilation system.

2.4 Energy balance

Residential buildings use energy for several purposes both in electricity and heat form. The energy balance is determined by the following equation which takes into account the supplied and the removed energy[11]:

$$Q_{energy} = Q_{heat} + W = Q_t + Q_l + Q_v + Q_{DHW} + Q_{dr} + W_f + W_h - Q_{rec} - Q_{int} - Q_{sol} \qquad (15)$$

Where the meaning of each parameter are the followings:

[11] Buildings and Energy - a systematic approach/ Formas 2007/ ISBN 978-91-540-5997-3

Q_{energy}: Annual net energy demand for normal and intended use of the building [W]

Q_{heat}: Annual net heating demand for normal and intended use of the building [W]

W: Annual electrical energy demand for normal and intended use of the building [W]

Q_t: Annual heat losses due to transmission through the envelope of the building [W]

Q_l: Annual heat losses due to air leakage through the envelope of the building including or caused by airing [W]

Q_v: Annual heat demand for ventilation [W]

Q_{DHW}: Annual heat demand for domestic hot water [W]

Q_{dr}: Annual distribution and control losses [W]

W_f: Annual electrical energy demand to run pumps, fans and extract air heat pumps as well as other domestic uses [W]

W_h: Annual electrical energy demand for domestic purposes [W]

Q_{rec}: Annual quantity of heat than can be recovered and returned to the building via ventilation heat exchanger, an extra air heat pump, solar cells, waste water heat exchanger or similar [W]

Q_{int}: Annual quantity of surplus heat that can be used to replace heat supplied to the building via so-called internal loads such as heat from occupants, the consumption of domestic electricity, from hot tap water and any other surpluses created in the building [W]

Q_{sol}: Annual quantity of surplus usable heat created by solar radiation through windows [W]

3 Method

3.1 General approach

Since this is a calibration process the following method has been carried out in which the information sources are hierarchized. According to this method the model should not be changed unless there is an evidence from a more reliable source in the source hierarchy [19].

Table 3: Evidence-based calibration methodology used in the thesis

Data-logged measurements	Indoor temperature diagram for the whole building Household electricity consumption in 2016 [kWh] District heating energy consumption in 2016[kWh] Heated hot water in 2016 [m^3] OVK
Short-term measurements	Temperature and RH loggers in common areas (basement and stairwells)Period: 04/04/2017 - 26/04/2017 Air-flow measurement in the apartments
Direct observation	Site visiting to Gråstensvägen 23-29 Through laser metering ensure if the drawings meet the dimensions of the building. Thermography camera to detect heat losses and temperature difference mainly in the basement. Lighting evaluation in common areas
Operator and personnel interview	Meeting with Gavlegårdarna personnel and collect some information about the district heating heat exchangers system and hot water circulation throughout the building.
Operation documents	Datasheets and O&M manuals of the machines in the laundry room.
Benchmark studies and best practice guides	Mainly used for the walls construction and materials
Standards	Sveby Standards for Tenants equipment ISO regulations for calculations Boverket Swedish buildings regulation ASHRAE guidelines

First of all the author has built the CAD according to the drawings provided, then based on the measured and provided data, the energy consumption has been obtained through IDA-ICE building modelling simulation tool. In order to get a more accurate model and get closer to the real building, thermal bridges have been calculated through COMSOL finite element software and use those values as input as well.

Moreover, some temperature loggers have been located in few areas of the building for a short-term measurement. The data collected have been analysed in order to check how large the climate effect in the indoor common areas is.

Finally, the comparison of space heating energy and indoor temperature values between the current data and the results will be carried out. This is called validation process, which plays the key role in the thesis itself. Besides, results will be discussed and compared to the standard values and to conclude, future outlook will be exposed.

3.2 Limitations

Throughout the thesis period the author has gotten through some limitations which might have influenced the calibration of the model. For this reason, some assumptions and estimations have been taken in order to move forward with the project.

Regarding to the construction of the building, the drawings obtained were from 1966 with no detailed description of the walls construction. Hence, based on case studies typical building drawings from that time or other sources of information, the materials and layers have been decided. It could be considered an approach to the real building, although it has not been an accurate method for building the model.

However, the plans for creating the CAD were pretty complete so there has not been any issue regarding to that, except with the balconies. The balconies are supposed to be inside the building but the software did not let it, though it has been assumed that with the thermal bridge related to the balcony, this heat loss has been taking into account.

In terms of internal gains, logically each apartment is different in the reality. Not everybody has the same electrical devices at home or consume the same quantity of energy, however to simplify, it has been assumed all apartments to be equal in all aspects: lighting, equipment, occupancy, heating and ventilation. In the end the average value is the evaluated one, so it does not have too much importance the private consumption of each apartment. The same occur with the schedules, typical use has been estimated. In fact, the most consuming apartments compensate to the ones that are sparsely occupied. District heating is the responsible for the heating system through hydronic radiators. Due to the lack of information, it has been assumed as ideal heater, which is a room unit that heats the zone and has a PI controller to keep the room air at the specified heating set point.

This building only has local mechanical exhaust ventilation system and it can be controlled by the occupants. Each person can manually vary the air flow of the apartment and is not an easy task to reflect this in a simulation program if there is not information about the behaviour of the occupants. Therefore, it has been assumed a constant air flow in a minimum value most of the time and maximum during the cooking period when more air extraction is required.

Finally, climate is also one of the most important factors for buildings' energy performance simulation program. The energy consumption of a building is definitely dependent to the weather. An attempt was made to import Gävle’s climate file (.prn) for IDA ICE, but due to numerical error while it was simulating, the author has chosen from the ASHRAE database the closest one to Gävle. Hence, the input has been Söderhamn’s normalized climate data which can be considered very similar to the location studied.

3.3 Building's performance assessments

3.3.1 Temperature and humidity loggers

Indoor temperature is one of the most influential factors to evaluate in the study of the energy performance of a building. It has been possible to obtain the mean indoor temperature data of all apartments during 2016 since zone thermostats with logger functions were installed in the buildings a couple of years ago. But there was not information about the basement area and the stairwells. Therefore some temperature and humidity logger have been located in several points of the building where it was that uncertainty. The logger have collected data for 22 days (04/04/2017- 26/04/2017) so it has been analysed the climate effect in the indoor temperature. 5 loggers have been situated in the following areas:

Table 4: Loggers location in the building

Loggers	Area
1	Basement Cold
2	Basement Warm
3	Stairs floor 0
4	Stairs floor 1
5	Stairs floor 2

Mitec loggers Satelite inaccuracy ±0.3 °C and ±3 % RH.

3.3.2 Thermography

Thermography can help to the study of thermal performance of a building envelope, it measures the surface temperature of any object that emits radiation. Thermography captures imperfection areas where large heat losses occur like thermal bridges and air leakages so for this reason it can provide representative results [20]. In the utilities room where the district heating heat exchanger is situated few images have been taken for the evaluation of the pipes where it was visible a great temperature difference between surfaces. Electrical devices have been captured as well because is obvious their temperature is higher, hence, the thermal radiation is higher as well.

The pictures below have been taken to the studied building. Figure 3.1 on the left shows the building's envelope from outside and it represents the large heat losses through the window. Thermal bridge between external wall and a window is pretty influential for the heat transmission losses. Besides, the below part of the window is colder this could be due to air-infiltration in that area.

Thermography camera has been also used in the laundry room where the window was open. Figure 3.1 on the right, reflects the influence of the laundry room airing and the temperature difference between indoor (26 °C) and outdoor (13°C). According to the colour of the wall, the temperature seems lower than what it should be. The brightest colours belong to pipes and washing machines.

Inaccuracy of the IR (infrared) camera is ±2 °C.

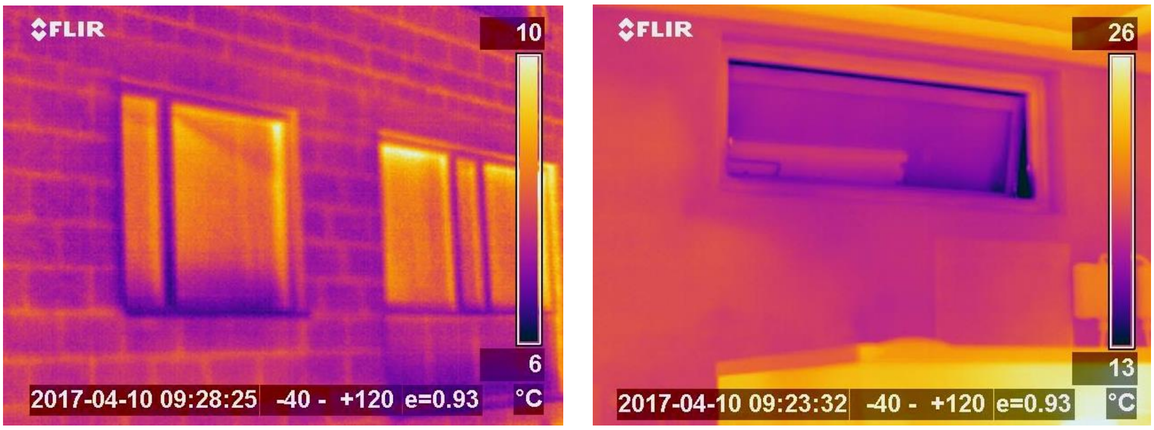

Figure 3.1:Thermography camera images to show heat losses

3.3.3 Ventilation measurements

It has been possible to enter in an empty apartment and measure the airflow through SwemaFlow instrument. This air flow hood is suitable for both high and low diffusers and it can measure supply and exhaust air flows. Regarding to the measuring principle, accurate value of the average air flow is given by a net of hot wires. Moreover, it has a big cross section that minimizes the restriction of the flow and when the hood is placed to an air terminal device the measurement value is sent instantaneously[12].

Table 5: SwemaFlow 4000 measurement uncertainty

Air Flow	3 -30 l/s : ±1 l/s or better at 20 ... 25 °C 30 -1500 l/s : ±3 % or better at 20 ... 25 °C ± 0.15 % per °C deviation from cal. temperature
Temperature	±0.4°C above 50 l/s ±0.6°C below 50 l/s
Barometer	±3.5 hPa

[12] SwemaFlow/ www.swema.com

Figure 3.2: SwemaFlow for measuring air flow

The ventilation of the apartments does not have supply air, there is only mechanical exhaust ventilation system. There is an air damper control in the kitchen where the flow distribution among the exhaust points of the apartment can be regulated by the occupant. Six measurements have been taken, three of them with the closed damper and the other three once it was opened. For each mode there are three states: minimum, level 1 and level 2. The exhaust air point are in the kitchen, bathroom and clothing room, as observed in the visited apartment.

3.4 IDA ICE

IDA Indoor Climate and Energy (IDA ICE) is a building energy simulation tool which can predict and analyse the performance of the buildings. IDA ICE creates a mathematical model where a simultaneous dynamic simulation of air flow and heat transfer are provided. Thus, based on the equations from ISO 7730 thermal comfort is predicted as well as the calculation of heating and cooling load of the buildings.

3.4.1 CAD

The studied building was built a long time ago and Gavlegårdarna could not provide the CAD file in order to import it in IDA ICE. Therefore, the building has been designed according to the drawings and measurements of the structure. In order to ensure that the drawings were correct the building has been measured and compared with the values. Once the drawings were considered valid by visiting the site and taking external measurements of the building with laser metering, then the model has been carried out.

Based on the direct observation and drawings a four floor building has been created: The basement has been divided in two different zones, the cold and the warm areas. The reason for this division is because the cold area is not heated, lighted or equipped at all and in the warm zone there are storage rooms for every apartment, the laundry room and the heat exchangers room. Therefore, the indoor temperature and moisture should vary significantly from the cold zone.

In the first floor, which is the ground connected floor, one zone per apartment, and other eight different zones for the stairs and entrances of each main door. The next floor, is formed by 12 apartment zones and another 4 for the stairs. The stairs have been divided in floors as well, due to the different indoor temperatures. The last floor has been distributed in the same way as the before mentioned.

3.4.2 Internal gains

Unknown internal gains have been designed based on Sweden's standard criteria for energy use in buildings according to Sveby:

> *"Sveby stands for "Standardize and verify energy performance in buildings" and is a Swedish cross-industry initiative to develop voluntary guidelines on energy use for contracts, calculations, measurements and verification"*[13].

<u>Occupancy</u>

According to Sveby if there is a lack of information about the occupancy of a building it is possible to estimate how many people are living in each apartment depending on the number of rooms; for 2 or 3 bedroom apartments the standard values are 1.63 and 2.18, respectively [21]. Since every apartment has different size, it has been assumed the intermediate value of 2 people for each apartment.

<u>Lighting</u>

Regarding to the internal gains typical household consumption has been assumed for the apartments due to the fact that there was not access allowed to the private area. According to the lighting, each zone includes 5 lamps of 30 W each, with an efficiency of 12 lm/W. The default house lightning schedule has been chosen for that case, where the lights are on during 10h per day. According to a case study, the lighting supposes around 20 % of total household electricity consumption [21]. In the model, has covered the 22%.

On the other hand, the lights of the warm area of the basement have been checked so the input in that case was exact to the reality. In this zone house lighting schedule has been selected as well. The detailed information about the lightning of the basement is added in the Appendix B – Measurements.

Based on the direct observation although there were some lights in the cold area of the basement, occupants do not have access to that area. So the schedule for that lighting has been assumed as "always off".

[13] Sveby - Brukarindata bostäder/www.sveby.org

Equipment

First of all is important to distinguish between tenants' equipment and facility equipment.

- **Facility equipment**: Facility equipment encompasses building's installations and all services for common use. Since the lowest consumption of an apartment has been 228 kWh which is a very low value and the laundry room is located in the common area, so is not easy to control how much energy has consumed each apartment, the laundry rooms' machines have been considered as facility equipment. Although in Sweden washing and drying consumption belongs to household electricity. Lighting of common areas, HVAC (Heating Ventilation and Air Conditioning) and pumps are also included in facility equipment.

- **Tenant equipment**: Tenants' equipment comprehend the electricity used for household purposes.

Regarding to tenant equipment, the basic electrical appliances has been taken into account with the following assumptions for energy consumption based on a reference case of Sveby standards:

Table 6: Energy consumption assumptions for household electrical devices

Electrical device	Power [W]	Schedule [h/day] all the days of the year	Energy use [kWh/year]
Fridge-freezer	82	24	718.32
Cooker	540	2	394.2
Computer	150	5	273.75
TV	150	2.75	150.56
Others:	30.64	24	268.41
Total Energy consumption in tenant equipment per year and apartment			1805.24

Schedules of each device has been estimated by the author. Therefore the total household electricity results in 2352.74 kWh as the sum of the lighting (547.5 kWh) and tenants' equipment (1805.24 kWh).

According to the standards value the total household energy consumption should be 30kWh/m^2 [21]. Since each apartment has different area, the average value of 80 m^2 has been taken into account. Which means that the model has been defined based on that value.

$$\frac{2352.74\ kWh}{80\ m^2} = 29.4\ kWh/m^2$$

For the facility equipment, during the visit to the building it was access to the laundry room and the collected data and their corresponding datasheets are available in Appendix C – IDA ICE. Besides, each person washes and dries 200 kg/year [21]. Taking into account the capacity in kg of the machines the washing times have been evaluated. For the consumption of the washing machines and dryers energy data of the datasheets have been used.

3.4.3 Windows

Almost all windows of the entire building have two pane glazing with a U-value of 2.9 W/m^2K as IDA ICE shows, which is a typical value for old buildings. The windows connected to the doors of the main entrances are one pane glaze instead. This has been verified during the site visiting as well as the size of the windows which meet the drawings' dimensions.

3.4.4 Wall constructions

For wall constructions information from different categories of the hierarchy before mentioned was collected. During the visit to the building, basement wall construction, external walls, roof and internal walls were inspected. In addition to this, through drawings, case studies and information collected about the construction of the old Swedish buildings the construction of the model has been as closest as possible to the actual building. The breaking-down of the wall constructions can be found at Appendix C – IDA ICE.

As it has been mentioned before, each apartment is formed by a zone. Nevertheless, inside there are internal walls which absorb heat during the summer and release it in winter period. This phenomenon cannot be neglected, so it has been taking into account as internal mass.

3.4.5 Room units

The whole heating system of the building runs by district heating, each apartment contains minimum of three water radiators. The assumption has been made based on the visited empty apartment. As it was not enough information regarding to the radiators, ideal heater have been assumed with a heating power of 10000 W for the whole zone.

3.4.6 HVAC (Heating Ventilation and Air Conditioning)

The air-flow of the ventilation system has been measured as well as it can be shown in Appendix B – Measurements. The ventilation system runs through a fan, so the air handling unit involves return air only. For the simulation Constant Air Volume (CAV) has been chosen, with a mean air flow of 20 l/s for the whole zone. In the reality, there are three out-flows in each apartment, in the kitchen, bathroom and in the clothing room. The ventilation can be regulated by the occupant with a minimum value of 18 l/s and a maximum of 42 l/s for the whole apartment. Assuming two hours of cooking time where the maximum air is extracted and the rest of the day maintaining in the minimum mode, a mean value of 20 l/s is obtained:

$$(18 \times \frac{22}{24}) + (42 \times \frac{2}{24}) = 20 \text{ [l/s]}$$

3.4.7 Other inputs

Infiltration air is another input for the simulation which has been estimated an air tightness of 0.5 ACH at pressure difference of 50 Pa which is the standard value for multi-family apartment blocks [21].

Regarding to the extra energy and losses section, in the heating system room there are two pumps which are working the whole year, the circulation pump and the tap water circulation pump with a nominal power of 0.18 kW and 0.25 kW respectively. This information has been collected during the site study.

For the domestic hot water, in Sweden each person uses between 50-70 l/day [22] and the standard energy consumption per square meter for an apartment block is 25 kWh/m2. The registered data for supplied hot water volume in 2016 was the following:

$$1746\ \frac{m^3}{year} \times \frac{1\ year}{365\ days} \times \frac{1000\ l}{1\ m^3} = 4784\ l/day$$

For the 34 apartments assuming 2 people in each one, the total tap water consumption per person per day results in:

$$\frac{4784}{34 \times 2} = 70\ l/day$$

In Sweden the supply temperature of the district heating grid is 5 °C and it is normally heated up until 55 °C. It has to be higher than 50 °C in order to avoid the risk of legionella. Therefore the energy required to heat up the tap water to the desired temperature is 101.3 MWh which has been the input value for IDA ICE.

$$1746\ \frac{m^3}{year} \times 1000 \frac{kg}{m3} \times 4.18\ \frac{kJ}{kg\ K} \times (55 - 5) \times 0.000277778 \frac{kWh}{kJ} = 101\ 365\ kWh$$

Assuming typical heat losses of 16 % through the hot water piping lines which means that the supplied energy for heating would be lower than the demand. If the energy used for both heating and hot water was 366.4 MWh, the space heating supply was 265.1 MWh. But since there is a space heating due to the heat losses through the tap water distribution pipes, the heating demand it would be slightly higher:

366.4 MWh district heating supply = 101.3 MWh + space heating supply Space heating supply = 265.1 MWh = heating demand – (0.16 * 101.3 MWh)	**Heating demand 281.3 MWh**

Therefore, the final value which has been compared to the measured data for space heating is 281.3 MWh. Besides, it has been assumed all the windows and doors to be closed during the whole year. However, the act of airing the apartments has been taking into account by estimating the Sveby's standard value for multi-family apartments of 4 kWh/m^2 [21]:

Final value to compare = result from IDA ICE for space heating + (4 kWh/m^2 *2895)

Where A_{temp} = 2895 m^2, which means the floor area heated up to more than 10 °C.

3.5 COMSOL

In order to get a more accurate model for the simulation, the thermal bridges have been calculated through the finite element software COMSOL Multiphysics. It has been studied the heat transfer in a composite two-dimensional structures assuming 1 m of wall depth. Linear thermal bridges have been calculated in different types of joints.

Calculation of Ψ-value has been carried out according to ISO 10211 regulation as it has been explained in the theory part. The process consists on obtaining the difference between the net heat flow throughout the real construction and the reference net heat flow. Assuming a temperature difference between indoor and outdoor of 1 K or 1°C.

For the conventional surface resistances in m^2K/W for horizontal heat flow the following values have been considered:

Table 7: Surface resistances for horizontal heat flow[14]

$\mathbf{R_{si}}$	0.13	[m^2K/W]
$\mathbf{R_{se}}$	0.04	[m^2K/W]

[14] Buildings and Energy - a systematic approach/ Formas 2007/ ISBN 978-91-540-5997-3

3.6 Indoor temperature measurements and thermography.

Indoor temperature is one of the influential factors to evaluate in the study of the energy performance of a building. It has been possible to obtain the mean indoor temperature data of all apartments during 2016 but there was not information about the basement area and the stairwells. Therefore some temperature and humidity logger have been located in several points of the building where it was that uncertainty. The logger have collected data for 22 days so it has been analysed the climate effect in the indoor temperature.

3.7 Validation

One of the most important parts of the thesis is the validation process. It plays the key role for the assessment of the simulation results and decide if they are reliable and valid. Once the results were obtained, the outputs from IDA ICE for the space heating consumption and indoor temperature of 2016 has been compared to the actual data provided by Gavlegårdarna. If the values are proximate in a 5% to the actual value they can be considered as valid.

4 Results

In this section most significant results have been explained to evaluate the building's energy performance and validate the model. Besides, there have been attached more results in Appendices.

4.1 Validation: actual consumption and the simulated results

From the provided actual data the electricity consumption and supplied volume of tap water has been known. The values of the simulation are almost the same to the real ones, so the important comparison is the energy consumed in space heating. Total district heating consumption in 2016 was 366.4 MWh which is the sum of space heating and tap water heating. Input data have been the household electricity 80.4 MWh and the energy required for heating up the tap water 101.6 MWh.

Table 8: Energy consumption comparison between reality and IDA ICE results

2016	Data (MWh)	Simulation (MWh)
Space heating	281.3	258.3

$$error\ (\%) = \frac{281.3 - 258.3}{281.3} \times 100 = 8.17\ \%$$

Is important to mention that IDA ICE does not take into account the airing of the apartments since the windows have been assumed to be always closed. This has influence for the space heating calculation, to which according to Sveby it could be attributed 4 kWh/m^2 [21]. For this reason it should be added that extra to the result obtained. For a Atemp = 2895 m^2

$$258\ 324\ kWh + \left(4\ {}^{kWh}/_{m^2} \times 2895\ m^2\right) = \mathbf{269\ 904\ kWh}$$

$$error\ (\%) = \frac{281.3 - 269.9}{281.3} \times 100 = 4\ \%$$

Therefore, the obtained energy used in space heating is almost the actual value. The error has been lower than 5 % so the model has been considered as valid.

4.2 Building thermal comfort

Thermal comfort can be evaluated through the following results at IDA ICE. On the one hand the main indoor temperature diagram and on the other the hand Fanger's comfort indices which illustrates PPD and PMV in the occupied areas.

4.2.1 *Mean indoor temperature*

The set point for the indoor temperature during the heating season has been 21 °C and the maximum mean temperatures registered in the apartments according to the results from simulation can be shown in the following graph:

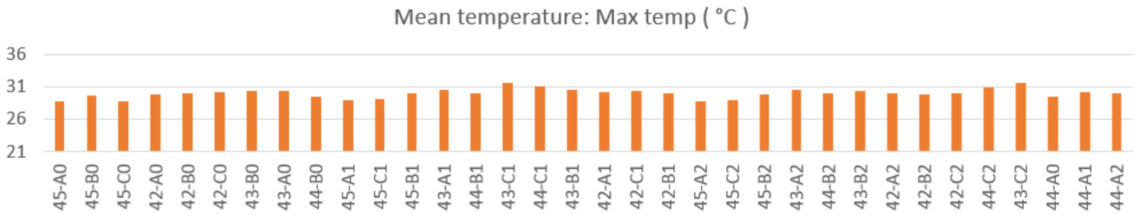

Figure 4.1: Maximum mean temperature of the apartments, IDA ICE

As Figure 4.1 shows, the average maximum temperature might be around 28 °C, and the in the worst apartment a little bit higher than 31 °C.

There are two charts representing the indoor temperature of the building throughout 2016. Figure 4.2 bellow represents the average indoor temperatures of all the apartments in the building, whereas Figure 4.3 shows the indoor temperature of one of the apartments of the model facing south-west located in the ground level exactly, 45-A0.

Figure 4.2: Measured mean indoor temperature diagram for the whole building in 2016

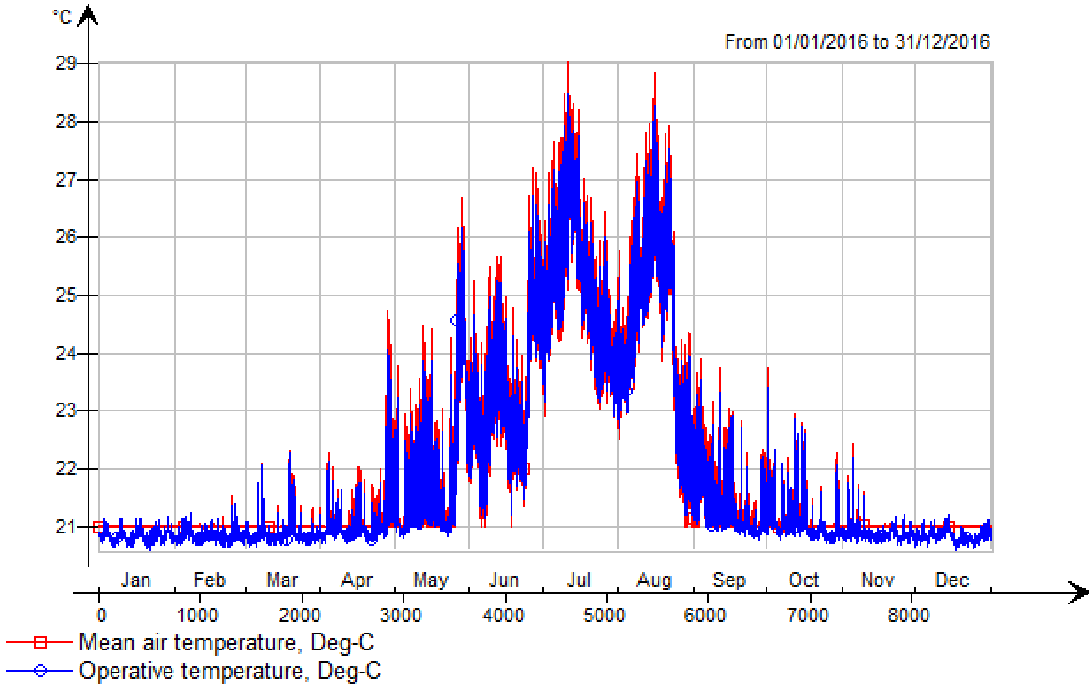

Figure 4.3: Mean temperature diagram of the apartment 45-A0 in 2016, IDA ICE

The results are reasonably similar during the heating season from January till May and from October in advanced where the control set point is at 21 °C. However summer period is quite tricky, in the reality the maximum value is almost 26 °C but on simulated results is reaching the line of the 29 °C. This fact, could be attributed to the airing of the apartments by the occupants when they feel thermal discomfort and decide to open the windows to let fresh air come in. Hence, the model is assumed to be correct and valid.

However, as it can be shown in Figure 4.2, in the reality the mean indoor temperature is higher than 21 °C. Therefore, it could be attributed this reason to the fact that the real energy use for space heating has resulted higher than in the simulation. In fact, it probably would be better to rise slightly the temperature set point in IDA ICE, although the lowest temperature registered in the measured diagram has been 21 °C.

Regarding to the operative temperature which is the one that measures how people perceive the thermal climate, according to Figure 4.4 where all the apartments have been analysed, the minimum operative temperature has been 21°C and the maximum 31 °C.

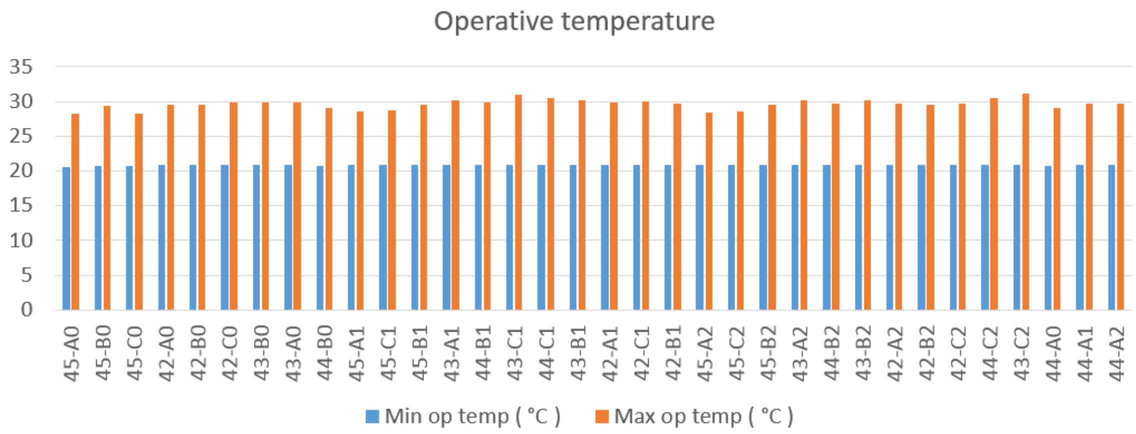

Figure 4.4: Minimum and maximum operative temperatures by apartments, IDA ICE

4.2.2 PPD and PMV

IDA ICE evaluates thermal comfort in the inhabited zones, in other words, in the apartments where occupants are.

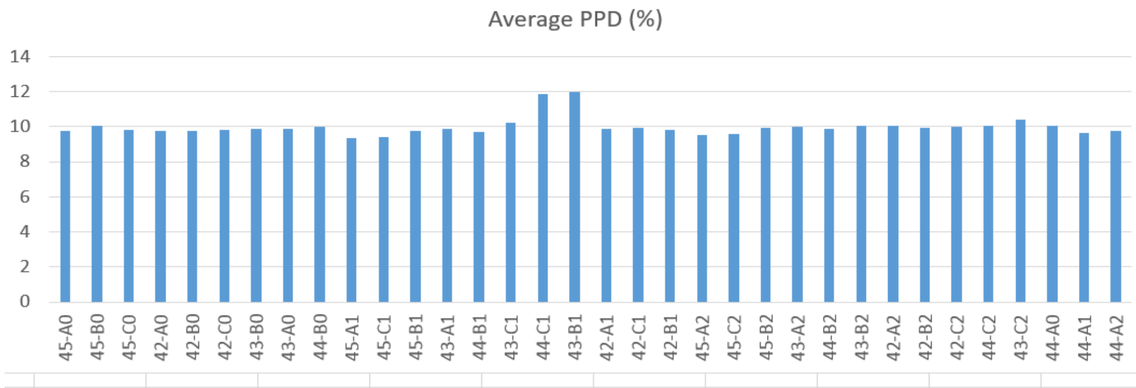

Figure 4.5: Average PPD by apartments, IDA ICE

As Figure 4.5 shows the worst PPD obtained has been 12% for the whole building but the average it is closer to 10 %, which is the limit for acceptable thermal comfort level. Although definitely results do not come close to the reality. It must be pointed out that all windows and doors have been assumed as closed during the whole year and any kind of ventilation or cooling system has not been considered. In the real life during the summer hot days occupants open the windows so fresh air can get in and cool down the environment. This increases the air flow rate of the apartments so as a result the indoor temperature reduces. In conclusion, real PPD is much lower, hence, higher thermal comfort level.

4.3 Thermal bridges calculation

As mentioned in the method, a detailed study of the thermal bridges of the building has been carried out. The comparison between IDA ICE's calculations and the hand-made ones have been analysed since the program has shown certain deficiencies for the thermal bridges in balconies and the floor connected to the ground.

Table 9: Linear thermal bridges calculation through COMSOL

Linerar thermal transmittance (Ψ value)	Total (W/m K)	Reference (W/m K)	Difference (W/m K)
External wall / internal slab	0,98245	0,75	0,23245
External wall / internal wall	0,78548	0,75	0,03548
External wall/ external wall	0,83092	0,75	0,08092
External windows perimeter	3,324	3,275	0,049
External doors perimeter	3,324	3,275	0,049
Roof/ external walls	0,6285	0,27633	0,35217
Ground slab/ external walls	**4,6929**	**4,2275**	**0,4654**
Balcony floor/ external walls	**6,6852**	**5,8**	**0,8852**
External slab/ external walls	4,6929	4,2275	0,4654

Then the manual calculation of the thermal bridges has been carried out. It is important to mention that the value calculated through finite element method for the slab junctions and the external – internal wall join has taken into account the floor in the above part and the ceiling in the below area of the slab. For this reason in some cases the obtained value has been divided by two as IDA ICE does, in order to approach to the simulated results. The areas used for the hand calculation has been the same as IDA ICE.

As it has been mentioned in the theoretical part for the calculation of the heat loss trough thermal bridges the transmittance must be multiplied for the length where these junction occurs all over the building. Afterwards, the total value would be multiplied by the temperature difference between outdoor and indoor.

Table 10: Thermal bridges hand calculation

Thermal bridges	Ψ value (W/m K)	Length (m)	Total (W/K)
External wall / internal slab	0,116225	764,1	88,808
External wall / internal wall	0,01774	320,89	5,693
External wall/ external wall	0,08092	136,87	11,076
External windows perimeter	0,049	989,6	48,491
External doors perimeter	0,049	24	1,176
Roof/ external walls	0,35217	188,25	66,296
Ground slab/ external walls	**0,2327**	**369,22**	**85,917**
Balcony floor/ external walls	**0,4426**	**65,22**	**28,866**
External slab/ external walls	0,2327	182,1	42,374
Sum			378,697

Thermal bridges	Area or Length	Avg. Heat conductivity	Total [W/K]
External wall / internal slab	1133.32 m	0.116 W/(m K)	131.692
External wall / internal wall	320.89 m	0.018 W/(m K)	5.693
External wall / external wall	136.87 m	0.081 W/(m K)	11.075
External windows perimeter	989.60 m	0.049 W/(m K)	48.490
External doors perimeter	24.00 m	0.049 W/(m K)	1.176
Roof / external walls	188.25 m	0.253 W/(m K)	47.677
External slab / external walls	182.10 m	0.465 W/(m K)	84.749
Balcony floor / external walls	0.00 m	0.000 W/(K m)	0.000
External slab / Internal walls	26.00 m	0.056 W/(m K)	1.451
Roof / Internal walls	337.02 m	0.056 W/(m K)	18.805
External walls, inner corner	74.66 m	0.000 W/(m K)	0.000
Total envelope (incl. roof and ground)	3896.36 m^2	0.000 W/(m^2 K)	0.000
Extra losses	-	-	-0.000
Sum	-	-	350.808

Figure 4.6: Results for thermal bridges, IDA ICE

External slab and roof with internal walls junction it has not been calculated through COMSOL due to the small relevance in comparison to the facade related ones. Apart from that, in the limitations section it has been stated that balconies were not possible to connect them to the building, for this reason IDA ICE has not been taking it into account. However, the author has made hand calculations for it as it can be shown in Table 10.

Besides, the building has internal floors of 300 mm of concrete but construction of the internal floor connected to the ground is completely different with a thickness of 700 mm. IDA ICE assumes all the internal floors to be the same, as a result the length should be reduced in a 1/3 for the external wall / internal slab thermal bridge. In this way only two internal floors would be taking into account as it is in the reality. On the other hand, the ground slab / external floor thermal bridge is not calculated through the simulation program but the author has made the calculation in order not to disregard its effect heat losses through building's envelope.

Therefore, the total thermal bridge values for the hand calculation and IDA ICE results have been the following:

Table 11: Comparison between thermal bridges' hand calculation and results from IDA ICE

Method	**Total (W/K)**
Hand calculation	398.953
IDA ICE	350.808

For the manual calculation, **(1.451 + 18.805) W/K** has been added to the value in Table 10, which corresponds to external slab/internal walls and roof/internal walls joins.

The error obtained it has been 12 % this value is quite high so it cannot be ignored because thermal bridges involves a significant share of the total heat-losses.

4.4 Transmission losses

Month	Walls	Roof	Floor	Windows	Doors	Thermal bridges
1	-12630.5	-2272.0	-759.8	-23910.0	-184.0	-6380.8
2	-11682.6	-2038.6	-1106.2	-22002.9	-164.0	-5771.9
3	-10174.2	-1613.8	-1602.3	-18942.1	-129.8	-4759.0
4	-8492.5	-1294.4	-1731.1	-16252.5	-99.7	-3980.7
5	-6094.0	-867.9	-2021.2	-12160.2	-57.1	-2707.3
6	-5294.7	-651.1	-1981.3	-10706.2	-41.2	-2314.6
7	-5060.4	-343.0	-1883.8	-10796.3	-44.4	-2291.2
8	-4691.7	-344.3	-1480.7	-10422.0	-45.6	-2286.1
9	-5383.4	-695.4	-949.0	-11327.2	-68.5	-2898.3
10	-7178.8	-1252.1	-851.8	-14695.0	-100.8	-3828.3
11	-9636.4	-1758.8	-721.4	-18843.7	-143.6	-5027.0
12	-12229.0	-2283.3	-800.9	-24201.7	-187.1	-6454.1
Total	-98548.3	-15414.7	-15889.5	-194259.9	-1265.7	-48699.3
During heating	-84622.2	-12090.0	-14363.9	-152756.5	-1108.0	-40546.5
During cooling	-10697.0	-2469.6	-1041.1	-34186.5	-124.9	-6503.9
Rest of time	-3229.1	-855.1	-484.5	-7316.9	-32.8	-1648.9

Figure 4.7: Building's envelope transmission (kWh) IDA ICE

There is a linear relation between the heat losses through thermal bridges and the thermal bridge heat heat-transfer coefficient. Therefore after some calculations the heat loss that belongs to thermal bridges according to the hand calculation has been 55382.8 kWh.

The share of the Table above has been illustrated in both cases, the IDA ICE results (the same as the Figure 4.7 shows) and the manually calculated one with the value that has just been mentioned.

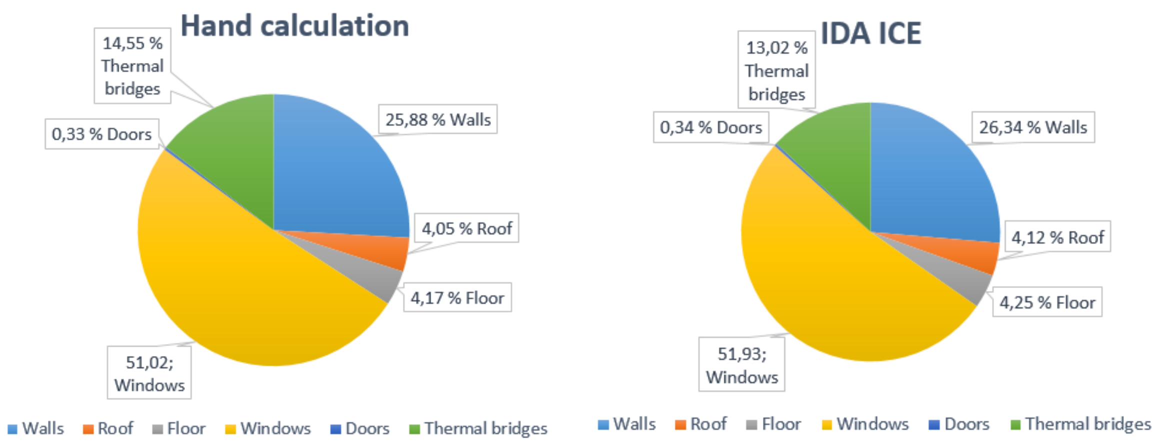

Figure 4.8: Breaking-down of transmission losses by hand calculation and IDA ICE results

Table 12: Transmission heat losses in 2016 through hand calculation and IDA ICE results (kWh)

	Walls	Roof	Floor	Windows	Doors	Thermal bridges
IDA ICE	-98548,3	-15414,7	-15889,5	-194259,9	-1265,7	-48699,3
Hand calculation	-98548,3	-15414,7	-15889,5	-194259,9	-1265,7	-55382,8

The highest transmission loss occurs through the windows, it suppouses more than the half of the total losses. Walls and thermal bridges are also quite relevant. The transmission losses through the floor and roof are quite similar.

4.5 Average U-value coefficient

Average U-value IDA ICE has calculated is 0.6757 W/m^2K. BBR states a value of 0.4 W/m^2K for new or retrofitted buildings [23]. Therefore, it is an understanding value for an old building but some improvements must be carried out in order to obtain a U-value lower than the maximum stated.

Table 13: IDA ICE results for transmission losses through building envelope

Building envelope	Area [m²]	U [W/(m² K)]	U*A [W/K]	% of total
Walls above ground	1169,82	0,44	518,42	19,69 (19,34)
Walls below ground	392,63	0,6	237,48	9,02 (8,86)
Roof	915,04	0,11	103,13	3,92 (3,85)
Floor towards ground	965	0,17	161,52	6,14 (6,03)
Floor towards amb, air	0	0	0	0
Windows	445,57	2,81	1252,04	47,56 (46,71)
Doors	8	1,13	9,05	0,34 (0,34)
Thermal bridges			350,81 (398,95)	13,33 (14,88)
Total	3896,06	0,68	2632,44 (2680,59)	100

The values added in parenthesis in Table 13, belong to the manually calculated thermal bridges. Therefore, the share has differed slightly towards the IDA ICE calculations.

Table 14: Transmission heat-transfer coefficient for IDA ICE and hand calculation

Transmission heat-transfer coefficient [W/K]	IDA ICE	Hand calculation
	2632.44	2680.59

Therefore the hand-calculated value for average U-value have been 0.6881 W/m2 K

4.6 Delivered Energy

	Purchased energy		Peak demand
	kWh	kWh/m²	kW
Lighting, facility	9254	2.5	2.52
Equipment, facility	12040	3.3	10.51
HVAC aux	4061	1.1	0.46
Total, Facility electric	25355	6.9	
District cooling	0	0.0	0.0
District heating	354550	96.0	137.7
Total, Facility district	354550	96.0	
Total	379905	102.8	
Lighting, tenant	18713	5.1	5.1
Equipment, tenant	61704	16.7	21.01
Total, Tenant electric	80417	21.8	
Grand total	460322	124.6	

Figure 4.9: Delivered energy overview according to IDA ICE results

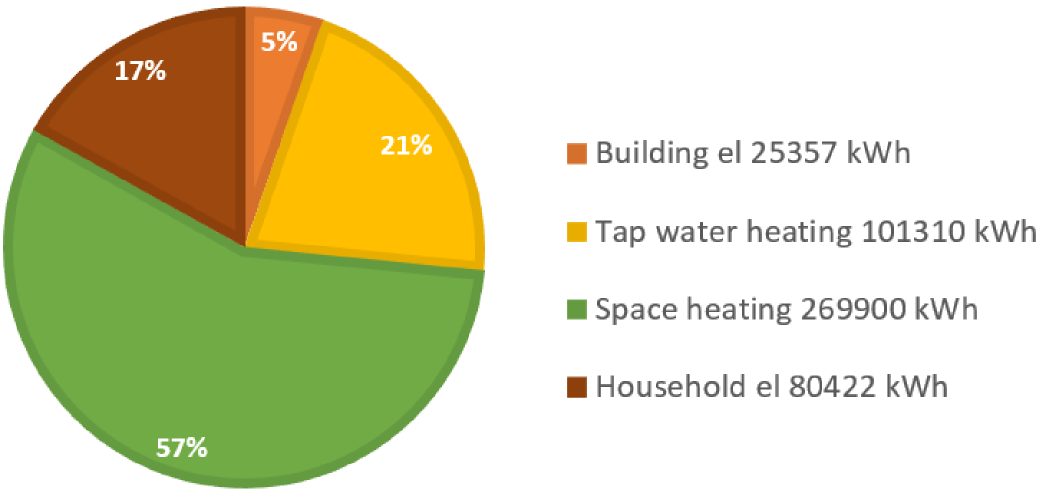

Figure 4.10: Breaking-down of the total energy consumption in 2016, IDA ICE

District heating comprehends domestic hot water and heating demand and it involves a huge part of the total energy use with a share of 78 %. Electricity has been split up in two sections, on the one hand building use where everything in common use is included, such as, the laundry room, lighting in corridors and stairwells as well as HVAC (Heating Ventilation and Air Conditioning system) and the electricity required for the pumps. On the other hand, household electricity which encompasses electricity consumption of the apartments.

4.7 AHU

The building has only mechanical exhaust ventilation system. IDA ICE has calculated the specific fan power (SFP) and result has been 0.67 which surpass the maximum accepted value of 0.6 [24]. Only one central system per apartment has been possible to model, but the actual apartments have 3 extracting points each.

4.8 Energy balance (sensible only)

kWh (sensible only)

Month	Envelope & Thermal bridges	Internal Walls and Masses	Window & Solar	Mech. supply air	Infiltration & Openings	Occupants	Equipment	Lighting	Local heating units	Local cooling units	Net losses
1	-22228.1	184.0	-21551.8	0.0	-16753.8	3490.2	6267.5	2369.9	48179.0	0.0	0.0
2	-20764.0	50.7	-17432.2	0.0	-15373.2	3201.4	5859.0	2217.5	42208.8	0.0	0.0
3	-18277.9	29.0	-10858.3	0.0	-12920.3	3407.5	6261.1	2373.5	29950.5	0.0	0.0
4	-15599.2	-183.2	-4466.0	0.0	-10913.1	3321.0	6049.3	2289.2	19462.5	0.0	0.0
5	-11748.1	-730.6	3433.7	0.0	-7715.5	3234.9	6241.7	2367.9	4885.0	0.0	0.0
6	-10283.5	-627.0	5277.5	0.0	-6766.0	2709.4	6030.4	2292.2	1346.9	0.0	0.0
7	-9622.8	499.1	4062.2	0.0	-6771.8	2504.6	6238.1	2375.0	673.8	0.0	0.0
8	-8848.9	763.8	2658.0	0.0	-6522.6	2700.3	6238.1	2377.5	598.0	0.0	0.0
9	-9994.6	514.8	-2855.1	0.0	-7546.7	3280.1	6024.3	2305.4	8255.0	0.0	0.0
10	-13212.3	201.1	-8548.3	0.0	-9914.4	3508.8	6237.7	2371.0	19332.6	0.0	0.0
11	-17285.9	175.3	-16126.9	0.0	-13025.9	3313.4	6039.0	2273.9	34598.8	0.0	0.0
12	-21954.6	82.5	-22281.2	0.0	-16793.0	3448.8	6258.3	2361.8	48835.6	0.0	0.0
Total	-179820.1	959.6	-88688.4	0.0	-131016.2	38120.2	73744.5	27974.8	258326.6	0.0	0.0
During heating (8784.0 h)	-152743.0	20812.7	-109709.9	0.0	-105090.6	27207.1	46117.7	14675.4	258284.4	0.0	0.0
During cooling (0.0 h)	-20835.9	-15821.0	17472.5	0.0	-21277.6	8825.3	22014.5	9633.7	0.0	0.0	0.0
Rest of time	-6241.2	-4032.1	3549.0	0.0	-4648.0	2087.8	5612.3	3665.7	42.2	0.0	0.0

Figure 4.11: Energy balance kWh (sensible only) IDA ICE

In Figure 4.11 shows the energy balance (sensible only) for the whole building. Regarding to the thermal losses the higher losses have been through envelope and thermal bridges followed by infiltration and openings and then window and solar. On the other hand, local heating units have been the ones that heated up most the building, what is logical since that is their function. Equipment, occupants and lighting also have influence in the building's heating up.

4.9 Loggers data

Data collected from the loggers have been useful to realize how much affects the climate in the indoor temperature. In the period where loggers were placed, the climate changed drastically from 15 °C to -5 °C in few days. For being April it is a pretty unstable profile though it has been interesting to appreciate how large it can be the range of indoor temperature and get a closer idea of how can be the thermal feeling in the common areas in winter time. For instance, in harsh weather the indoor temperature of the stairwells decreased until 13 °C. Whereas, during the highest outdoor temperature the value differs in 10 °C more. At the same time, moisture has increased drastically until almost 60 % of relative humidity in the cold area of the basement and in the stairwells it has crossed the 45 %. This definitely can result in damage of the building materials and what is more important, occupants' discomfort.

5 Discussion

As it has been mentioned in the results, the calibration process has been successful with a valid model for the studied building. This model has been carried out on behalf to Gavlegårdarna because the building will be retrofitted in the near future and through the present model the impact of several energy saving measures in the building's energy performance will be studied. This task is not author's concern but the assessment of the building it is.

There are standardized values stated by Sveby as it has been mention throughout the report. On the one hand it has been concluded that the hot water consumed by the occupants of this building is higher than the normal, with an energy use of 35kWh/m^2 when the standard value is 25 kWh/m^2. On the other hand, household electricity has been assumed without the clothes washing and drying, which is understandable to have lower energy use that in the standardize value, where it is included. The standard value is 30 kWh/m^2 and the studied building's energy use of 28 kWh/m^2. Both this values, have been based on measured data.

To conclude with the validation process, a 8 % of difference between the measured data and simulation results is a bit high but it might be acceptable since there have been many sources of uncertainty. In fact, it has been assumed windows and openings to be always closed, which in the reality does not happen. So, by adding an extra of 4 kWh/m2 to estimate the occupants' behaviour of opening the windows for airing the apartments, the energy use for space heating has been closer the actual consumption with a 4 % of error. The obtained value has been 269.9 MWh when the energy demand for heating in 2016 was 281.3 MWh. There are many sources of uncertainty that can influence the results, such as the behaviour of the occupants with regarding to window's shading. It has been considered an integrated window shading with blinds between panes which is controlled depending on the sunlight. However, there are other cultural or personal factors that are unknown and have been ignored.

Regarding to the evaluation of the thermal bridges in which great attention has been shown throughout this thesis, IDA ICE have considered them mainly between typical and poor even approach to very poor in some joints. The construction carried out during the "Million Programme" period was not as advanced as it is nowadays. At that time thermal comfort was the priority more than energy saving. According to the manual calculation the thermal bridges have supposed almost 15 % somewhat less than the usual value, which is between 15-20%.

Thermal bridges has represented a 14.58 % (hand calculation) or 13.05 % (IDA ICE) of the total heat losses through building's envelope. As it has been mentioned in the results, IDA ICE has shown certain limitations when entering the values of thermal bridges. The balconies outside the building have only had an effect on the solar shading effect but have not detected any value for the thermal bridge. For this reason, a manual calculation has been carried out both for this case and for the internal floors. It has been sufficiently explained in the previous section, just as the impact on general heat losses has been demonstrated. The difference of these small details results in an error of 12 % with a rising of 6683.5 kWh per year of heat losses, reason why is important to take them in account.

The losses of heat transmission through the building envelope are very relevant in terms of heating demand. A large amount of heat is released through the windows about 51 % of the total losses of transmission logic value since they have a U-value of 2.9 W/m^2 K and suppose 11.4 % of the building envelope. On the other hand, it has been assumed that the ground below the basement is not insulated so that losses on the walls are also have been considerable with a share of 26 %. Thirdly there are the thermal bridges followed by the floors, roof and doors. But is not only about the transmission losses, it must also been point out infiltration losses since the energy lost through air infiltration and openings is not so far from the transmission losses.

Specific energy use for the building has result in 126 kWh/m^2 (Figure 4.9) per year where the area is referred to A_{temp} and the average thermal transmittance 0.6757 W/m^{2}K (Figure 8.29). For new or retrofitted buildings this values must be reduced at least until 100 kWh/m^2 for the specific energy use and 0.4 W/m^2 K for the U-value. Therefore, is evident large changes must be carried out for the energy performance improvement of the building although they can be considered quite common values for old buildings.

About the thermal comfort, in both cases real and IDA ICE diagrams, can be appreciate peaks during hottest months, sun irradiation hits intensely at this period and many hours per day and this results in a higher temperature inside the building. Nevertheless, as it has been mentioned before, occupants need air flow movement and fresh air in their apartments so airing takes part especially in summer. In fact, the simulating program has not taken into account this phenomena and that is the reason for those high indoor temperatures which unquestionably results in thermal discomfort for the occupants. As Figure 4.5 shows, 12 % (average PPD in the worst apartment) of thermal dissatisfaction it cannot be overlooked, even if in the reality might be lower it would be interesting to reduce this percentage. According to ASHRAE a PPD <10% is an acceptable value for thermal comfort.

Thermal comfort has been only evaluated in occupied areas, logically. Though, through the loggers placed in the stairwells and basement, pretty low temperatures have been registered during cold days. Especially in the cold area of the basement, moisture relative humidity increased drastically at the same time as the temperature dropped. This results, affects to the whole building and construction materials could deteriorate and end up in colder floor for the ground level or condensation problems.

Once results have been discussed, several retrofit options can be considered for the reduction of energy demand. First of all, a large transmission heat-loss is through the windows, exactly a 51 % of the share (hand calculation). By replacing the existing windows with high-performance glazing systems and window frames the U-value could be reduced considerable. In addition, the facade must also be repaired as the author during the visit to the building noticed certain cracks and areas in which the bricks of the inner layer of external walls were visible. It may also be interesting to seal the joints and intersections of the balconies or other areas where there are thermal bridges. Moreover, adding a new insulation layer on the walls facing outside would improve as well noticeably the average thermal transmittance. Besides, for the ventilation system it might be interesting to think about a heat recovery unit, hence the heat losses due the apartments' airing would be considerably reduced.

6 Conclusions

To conclude with this thesis, after the tuned of some parameters in IDA ICE, the built model has been considered as valid since the error obtained has been lower than 5 % (Once the standard value of 4 kWh/m2 has been added). This means that it can be used in the future to identify and estimate energy-saving measures for the retrofitting process. As far as building's energy performance assessment is concerned, the biggest share of heat losses belongs to transmission losses followed by air-infiltration and openings. More than the 50 % of the losses through building's envelope occur through the windows. Walls suppose a big share of the building's envelope so the heat losses through the walls are also considerable. Roof and floor accounts around 4 % each, of the total transmission losses.

Regarding to the energy breakdown, space heating has accounted a 57 % and the hot tap water 21 % of the total delivered energy. Household electricity has accounted 18 % and the building use electricity 5 %. Nevertheless, it has to be pointed out the energy belonging to building use it should be pretty higher, since it is also needed for maintaining the building's functions. On the other hand, the basement cold area has a high relative humidity which affects to the whole building and might influence in the cooling of the slab in the ground level which may result in occupant's discomfort. Finally it is not feasible to fully evaluate the performance of a building since there are several sources of uncertainty, such as, occupants behaviour and air leakage among others, also known as “performance gap” that can only be interpreted as assumptions or estimations of reality. Nevertheless, through BEPS (Building Energy Performance Simulation) tools it can easily carry out a simulation for any changes in the building and study its effect on the building's energy performance.

Outlook

There are several ways for improving the buildings' energy performance, retrofit of the building among them. In order to carry out this process, a model is needed for tuning some parameters and evaluate the influence of them towards the energy demand. To save energy more efficient systems should be implemented which are environmentally friendly. Gävle's public housing company, has taken action on this matter since it is a large energy consumer, with 200 million kr per year. The ambitious target is to reduce the energy use by a 20 % between 2009 and 2020. The retrofitting process of this building is a part of the process for achieving that air.

The first stage towards Gavlegårdarna's goal in relation to the multi-family block in Gråstensvägen 23-29 has been done and is now in the hands of the person who will continue with this project and who will carry out a major renovation for this building. Obviously it needs some enhancements, but this housing company has experience with other buildings that were built at the same time as the studied block so most efficient and economical measures for this kind of process might be known.

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8 Appendices

Appendix A – COMSOL results

External wall - external slab thermal bridge

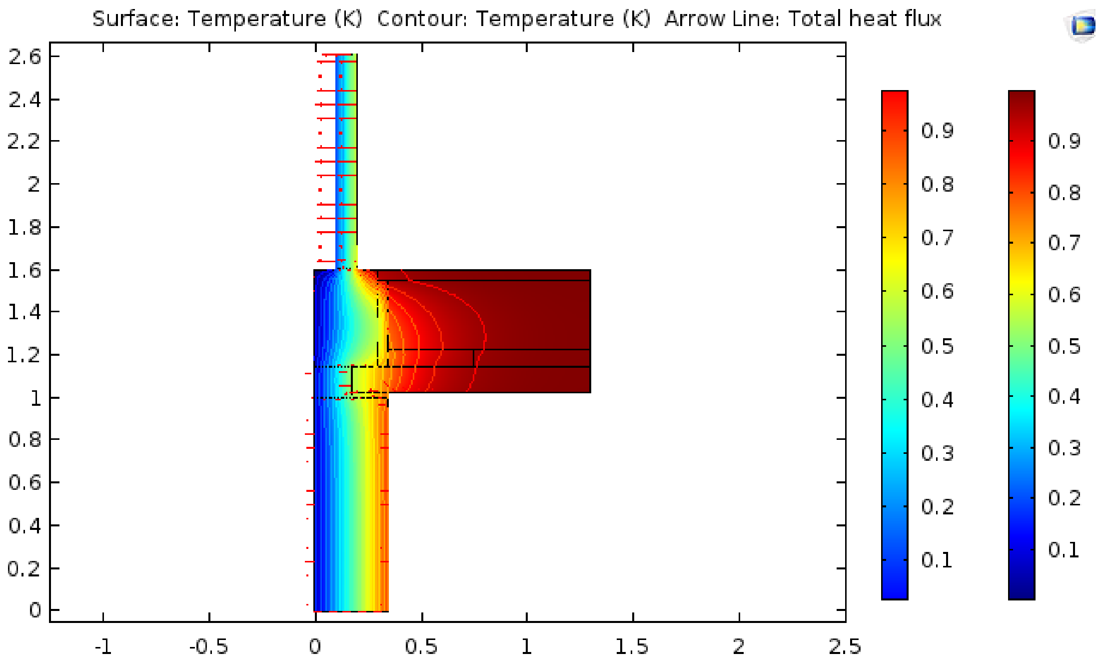


Figure 8.1: External wall – external slab total, COMSOL

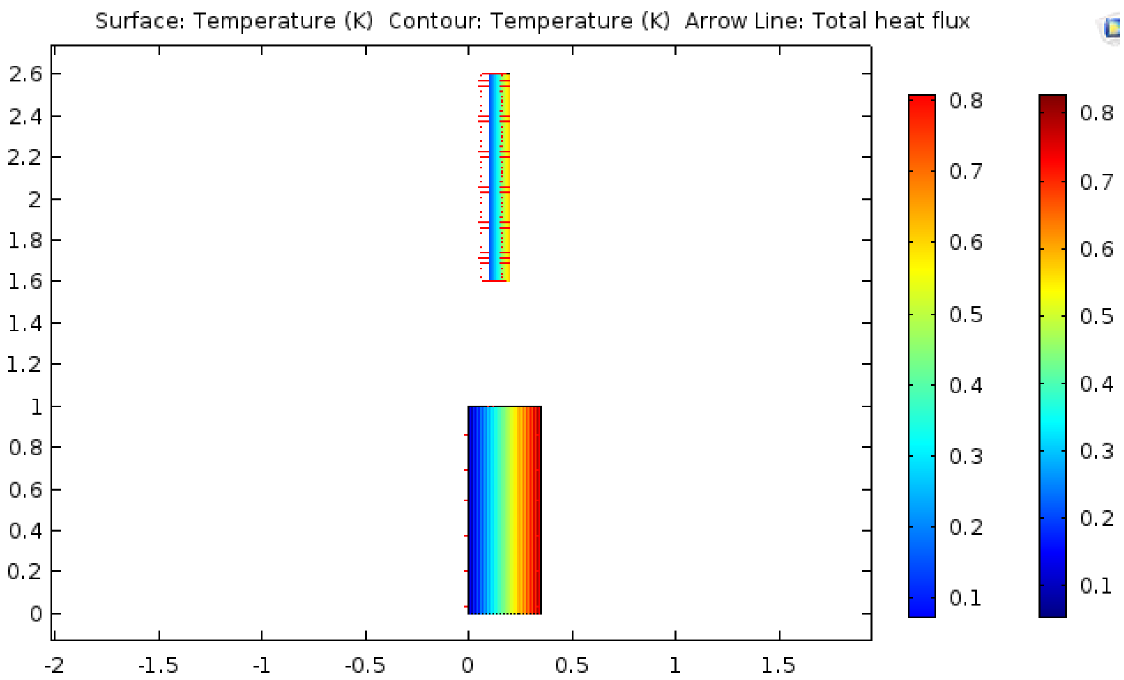


Figure 8.2: External wall – external slab reference heat flux, COMSOL

External wall – external wall thermal bridge

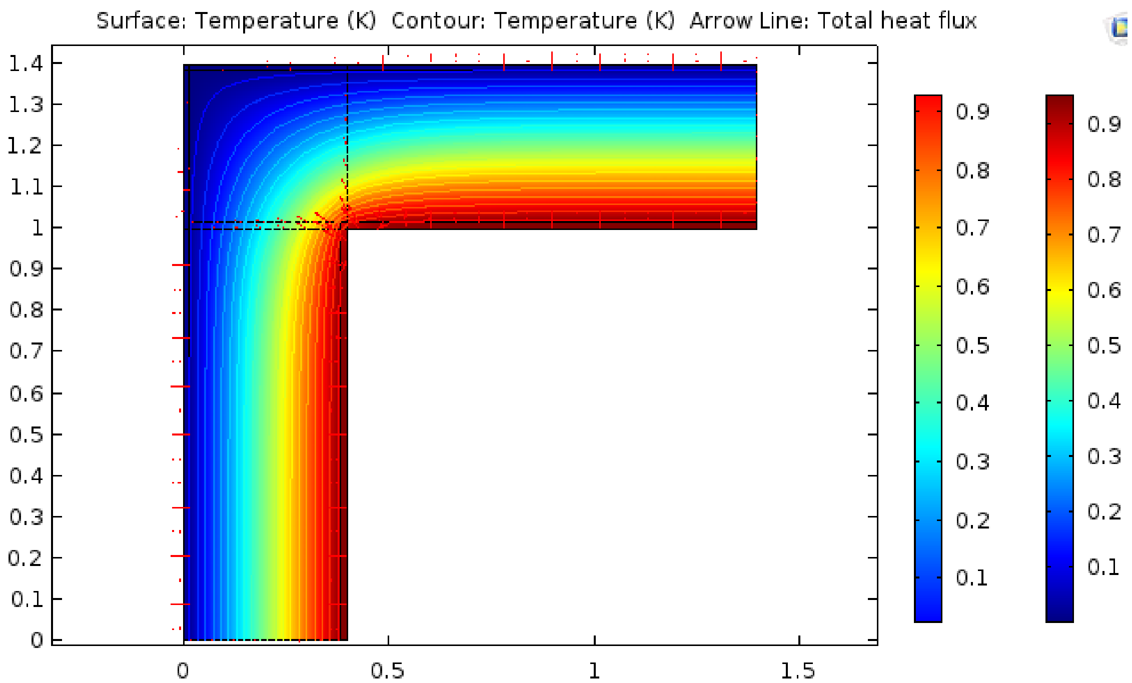


Figure 8.3: External wall – external wall corner total, COMSOL

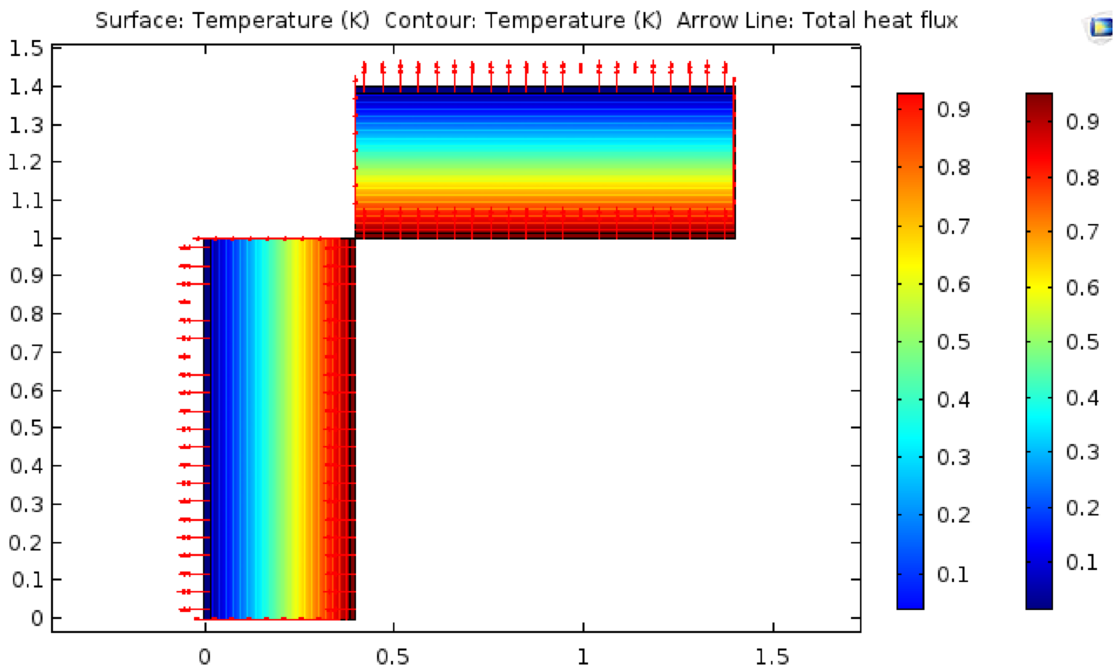


Figure 8.4: External wall – external wall corner reference, COMSOL

External wall – internal slab thermal bridge

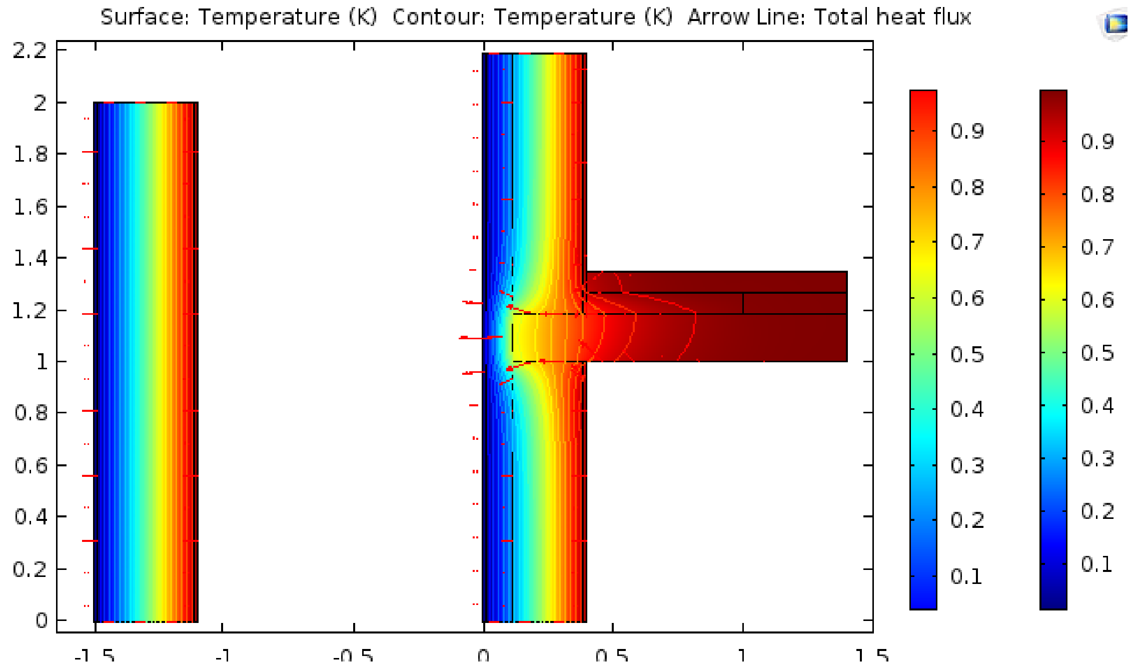


Figure 8.5: External wall – internal slab total and reference, COMSOL

External wall – internal wall thermal bridge

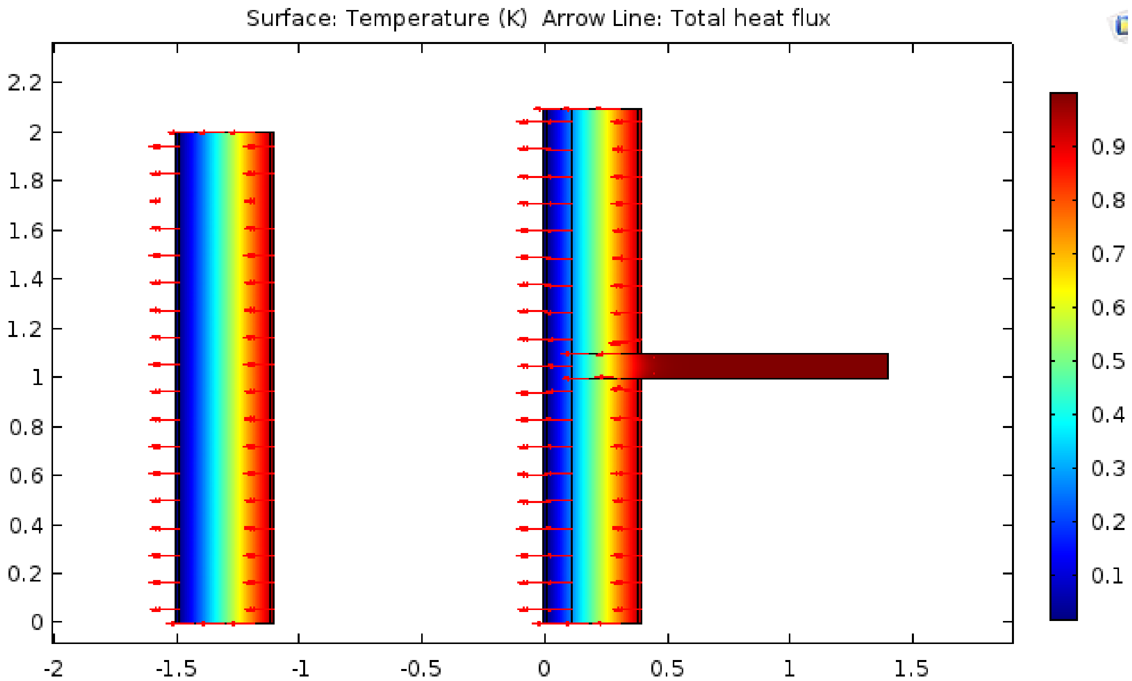


Figure 8.6: External wall – internal wall total and reference, COMSOL

External wall – roof thermal bridge

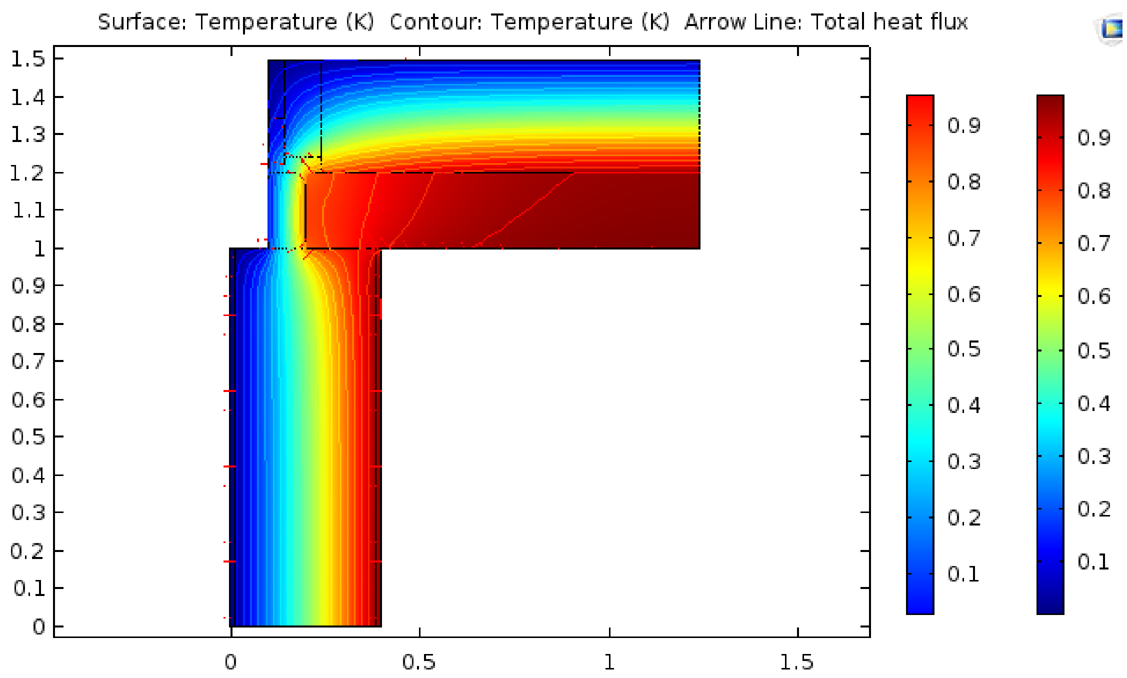


Figure 8.7: External wall – roof total, COMSOL

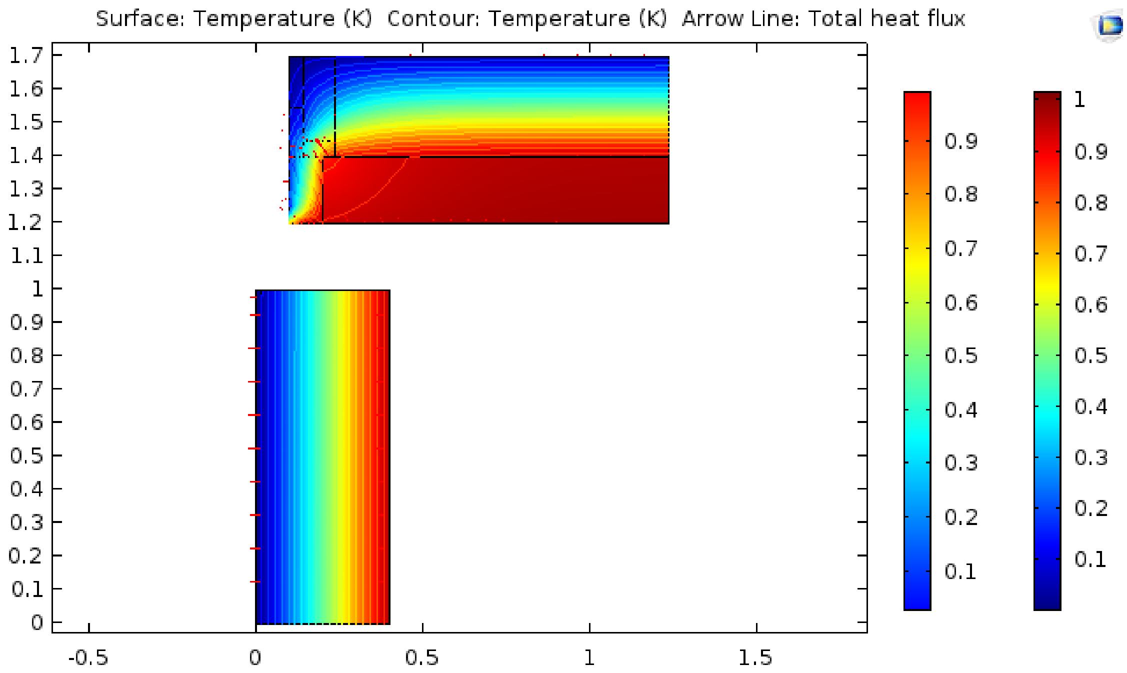


Figure 8.8: External wall - roof reference, COMSOL

External wall – window thermal bridge

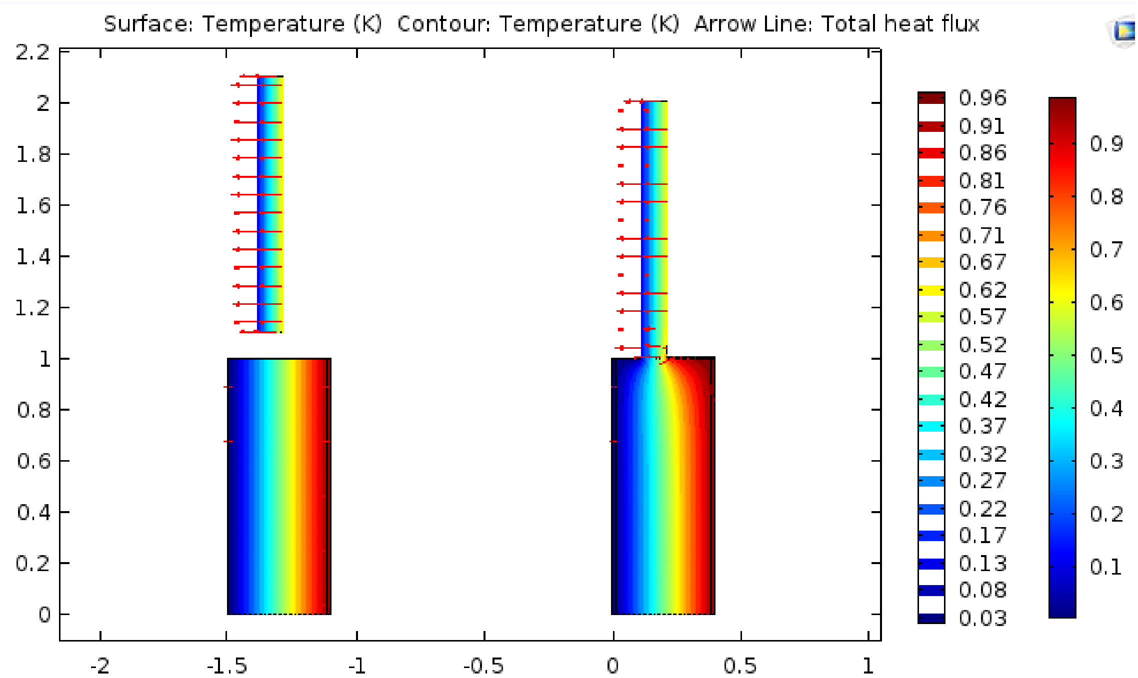


Figure 8.9: External wall - window total and reference, COMSOL

Slab – balcony thermal bridge

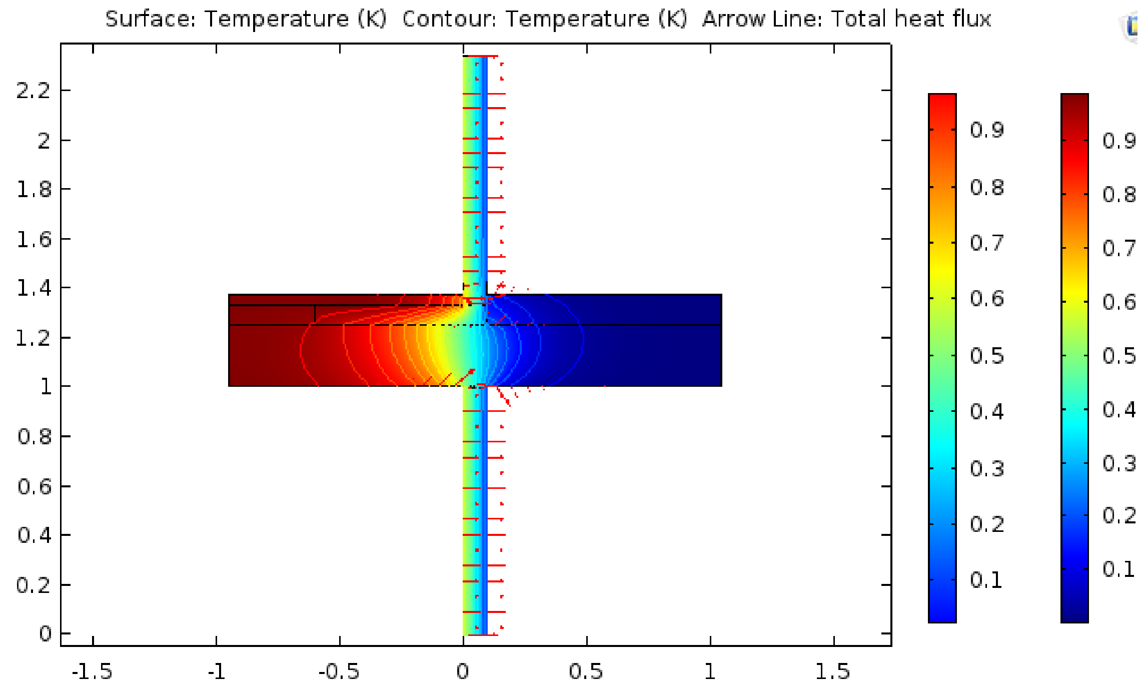


Figure 8.10: Slab - balcony total, COMSOL

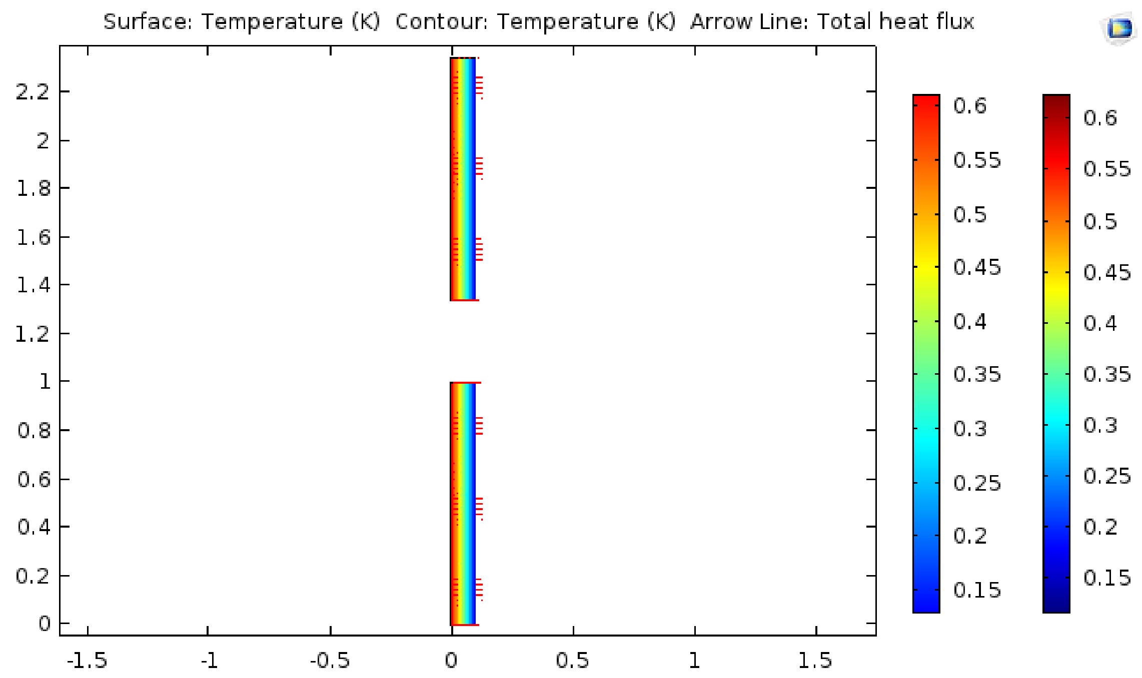


Figure 8.11: Slab - balcony reference, COMSOL

Appendix B – Measurements

Lighting

Table 15: Measured lighting in common areas

Lighting common areas	Power [W]	Lighting type	Nº
Basement cold	9	Fluorescent	3
	13	Low energy	1
	42	Halogen	4
Basement warm	9	Fluorescent	17
	13	Low energy	5
	72	TLD	7
Stairwells	9	Fluorescent	12
	13	Low energy	12

Ventilation

Table 16: Ventilation measurements in an empty apartment

	Control set point	Kitchen air-flow [l/s]	WC air-flow [l/s]
Damper Close	min	8	6
	1	13	9
	2	14	7
Damper Open	min	15	3.2
	1	27	5.8
	2	32	7

Loggers

Logger 1

Average temperature (° C) : 16.6

Average RH (%) : 42.5

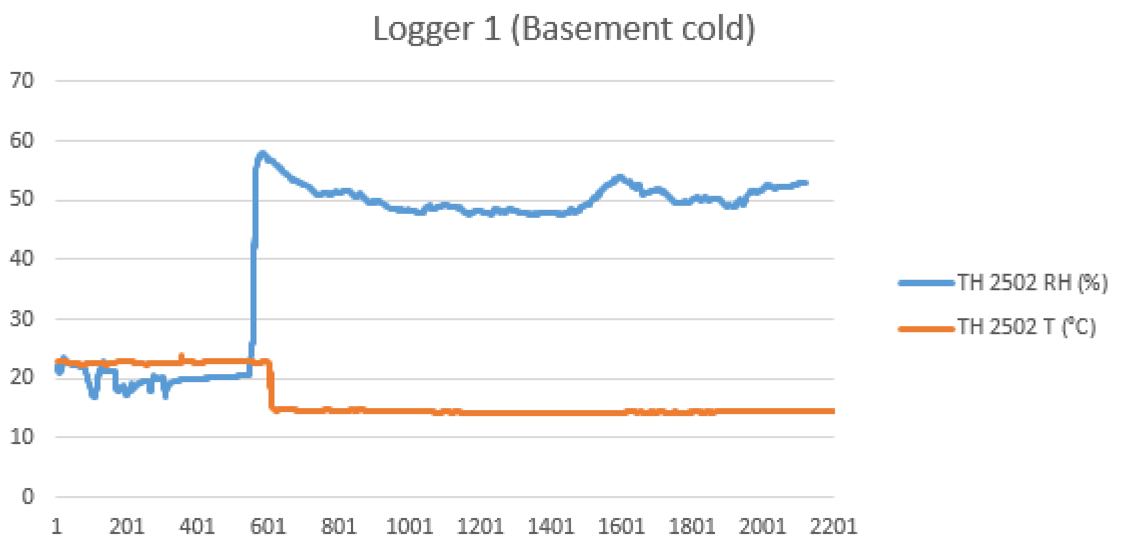


Figure 8.12: Data collected in basement cold (interval: 15 minutes)

Logger 2

Average temperature (° C) : 17

Average RH (%) : 33.1

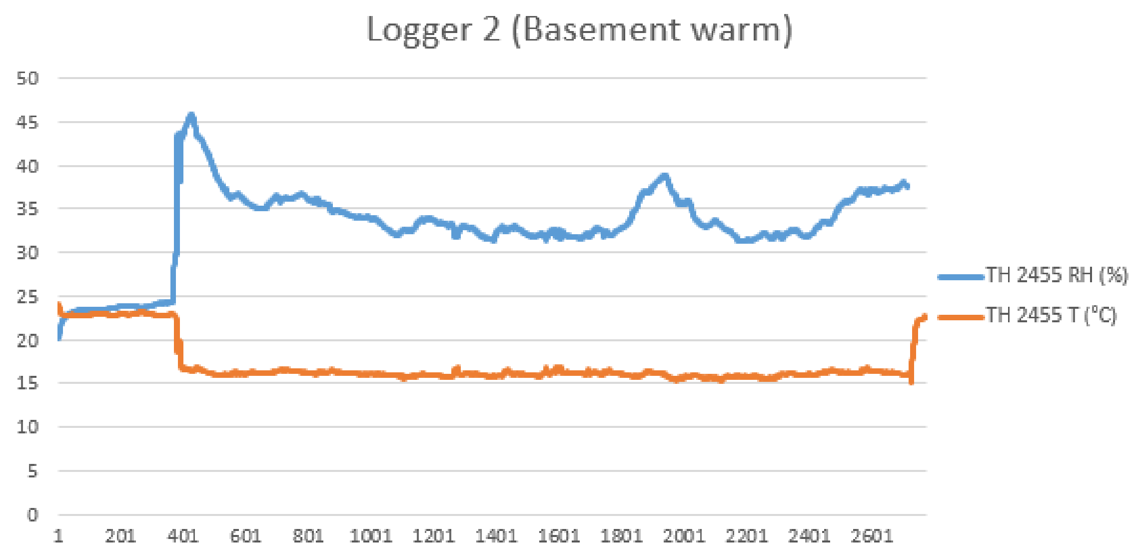


Figure 8.13: Data collected in basement warm (interval: 10 minutes)

Logger 3

Average temperature (° C) : 17.7

Average RH (%) : 25.7

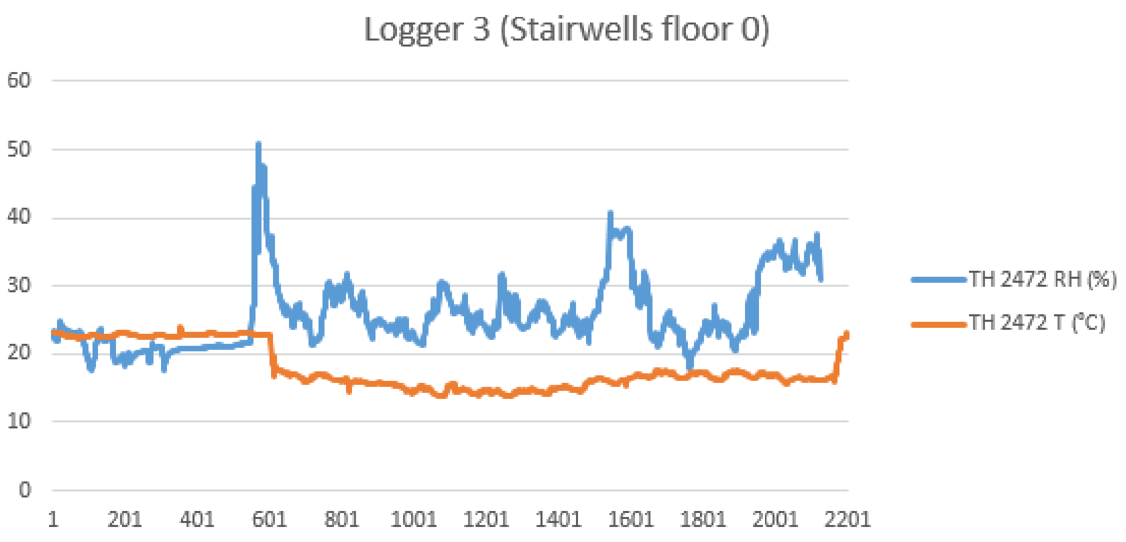


Figure 8.14: Data collected in Stairwells floor 0 (interval: 15 minutes)

Logger 4

Average temperature (° C) : 17.7

Average RH (%) : 42.5

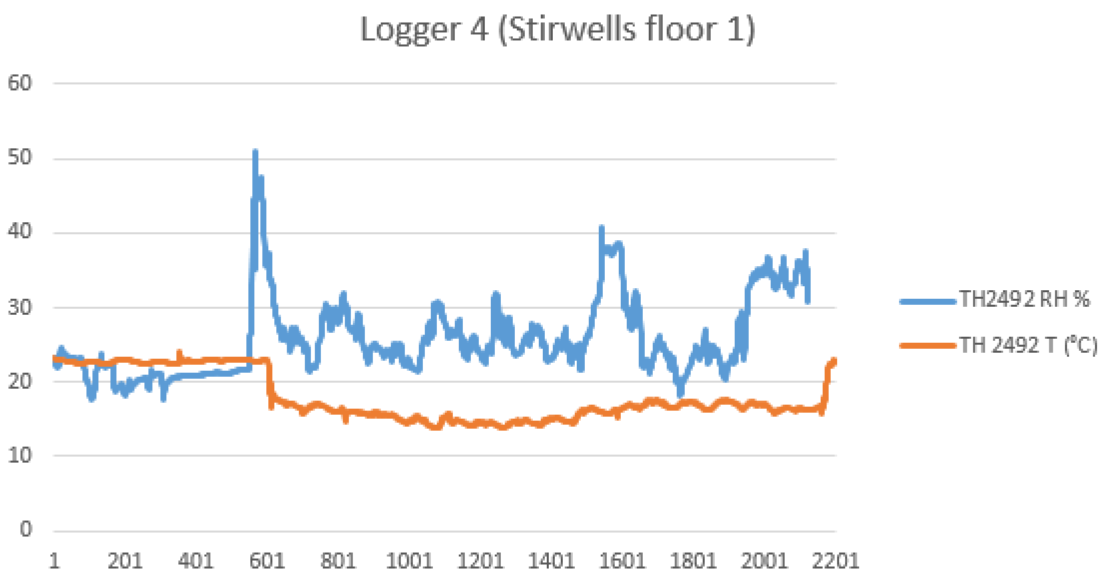


Figure 8.15: Data collected in Stairwells floor 1 (interval: 15 minutes)

Logger 5

Average temperature (° C) : 20.3

Average RH (%) : 24.9

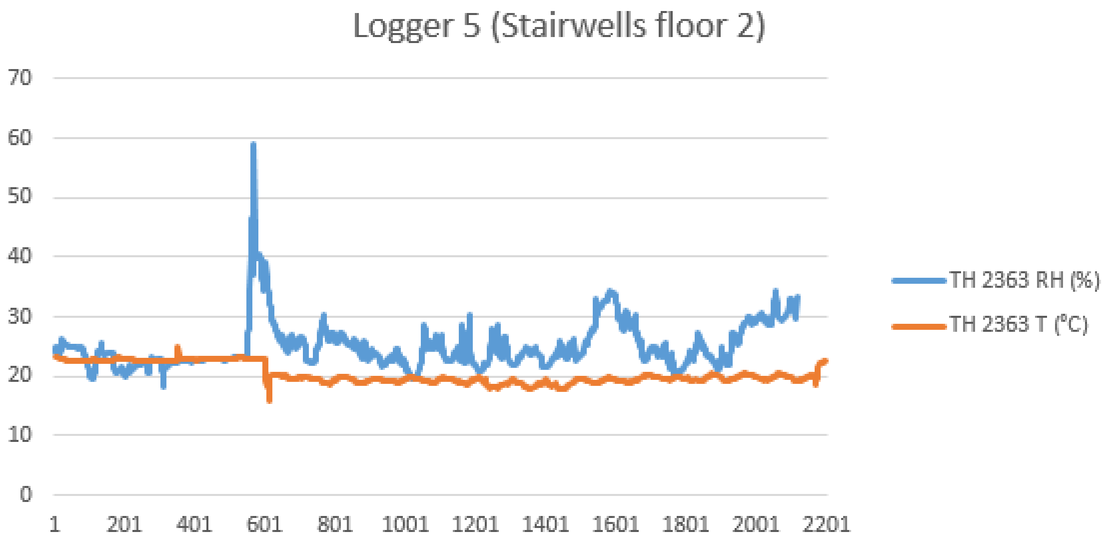


Figure 8.16: Data collected in Stairwells floor 2 (interval: 15 minutes)

Photos of the site

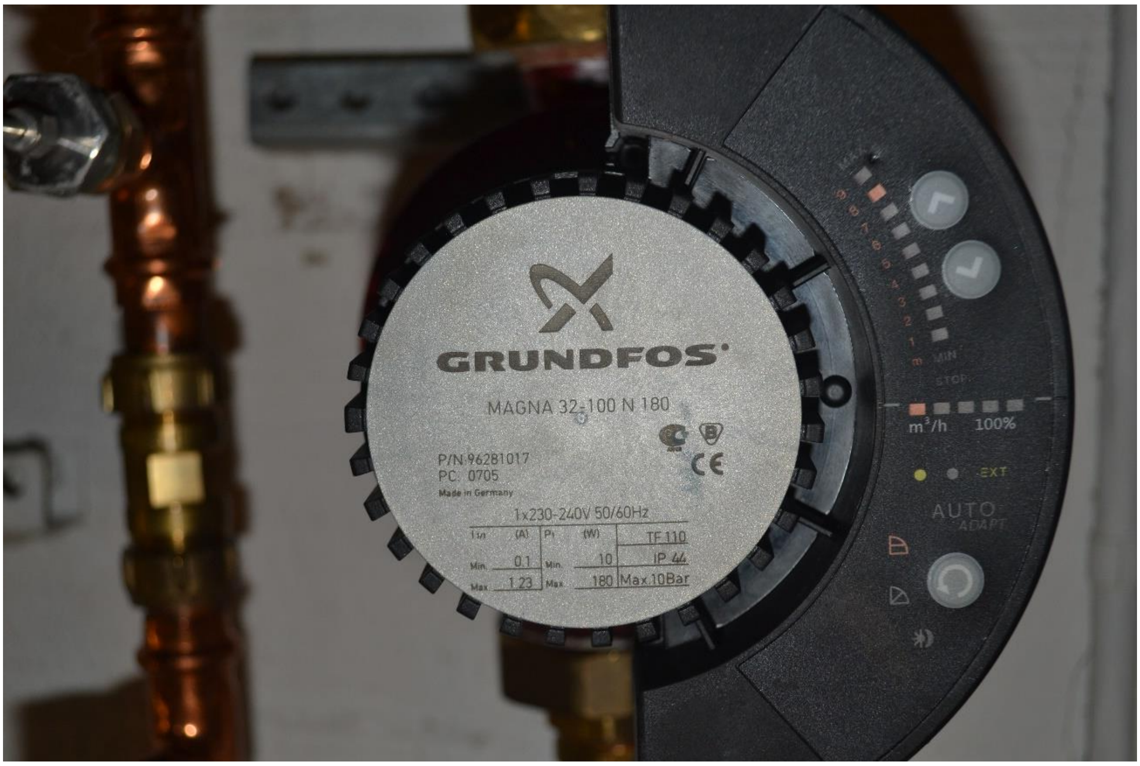


Figure 8.17: Circulating pump

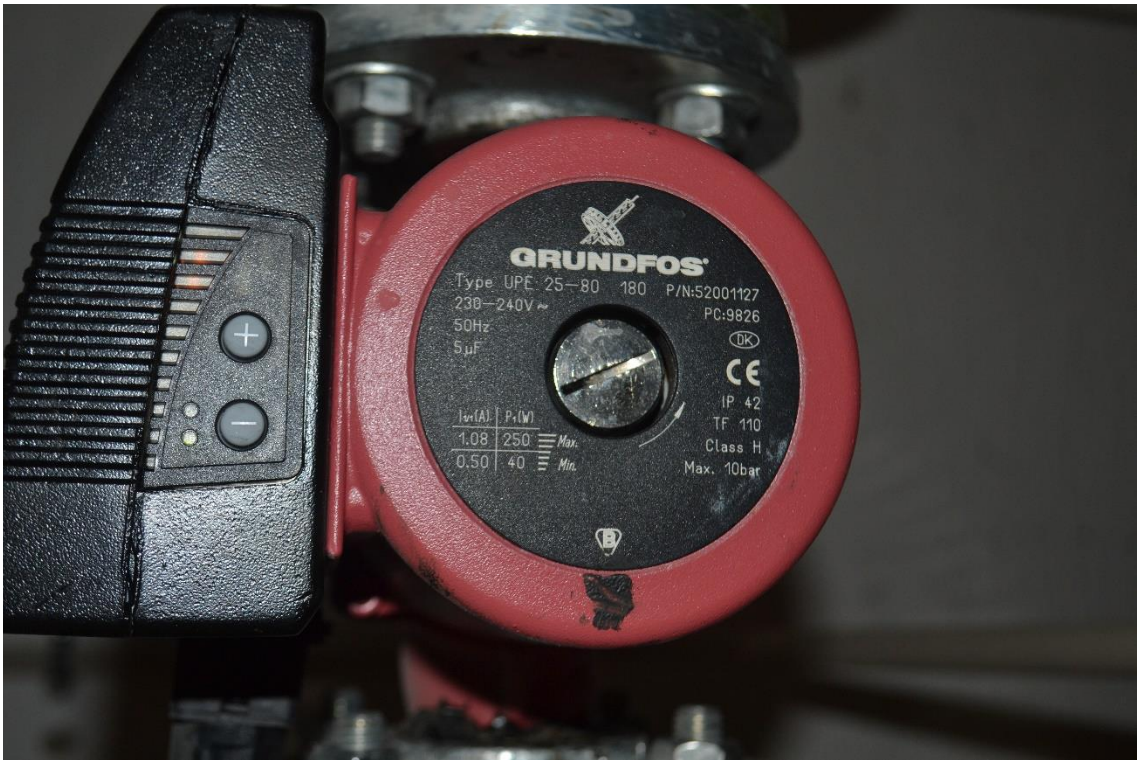


Figure 8.18: Tap water circulating pump

Figure 8.19: Hollow block, betonghålblock (basement wall)

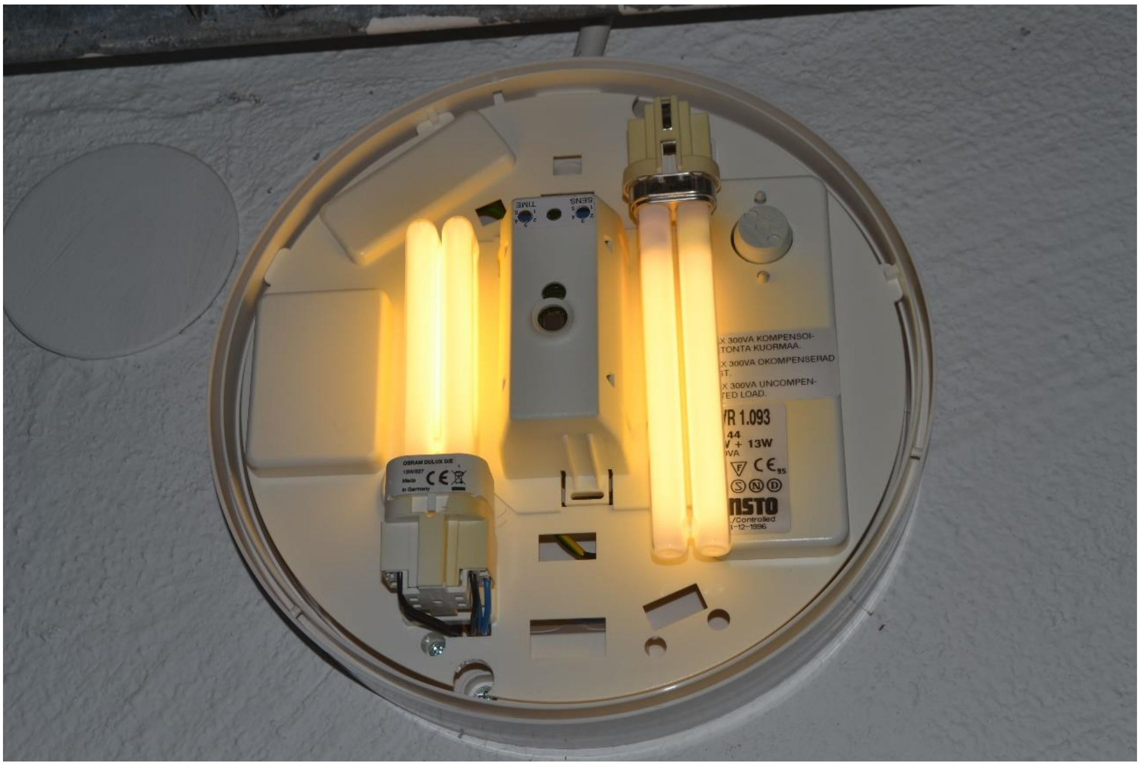


Figure 8.20: Basement warm lighting

Figure 8.21: Laundry room

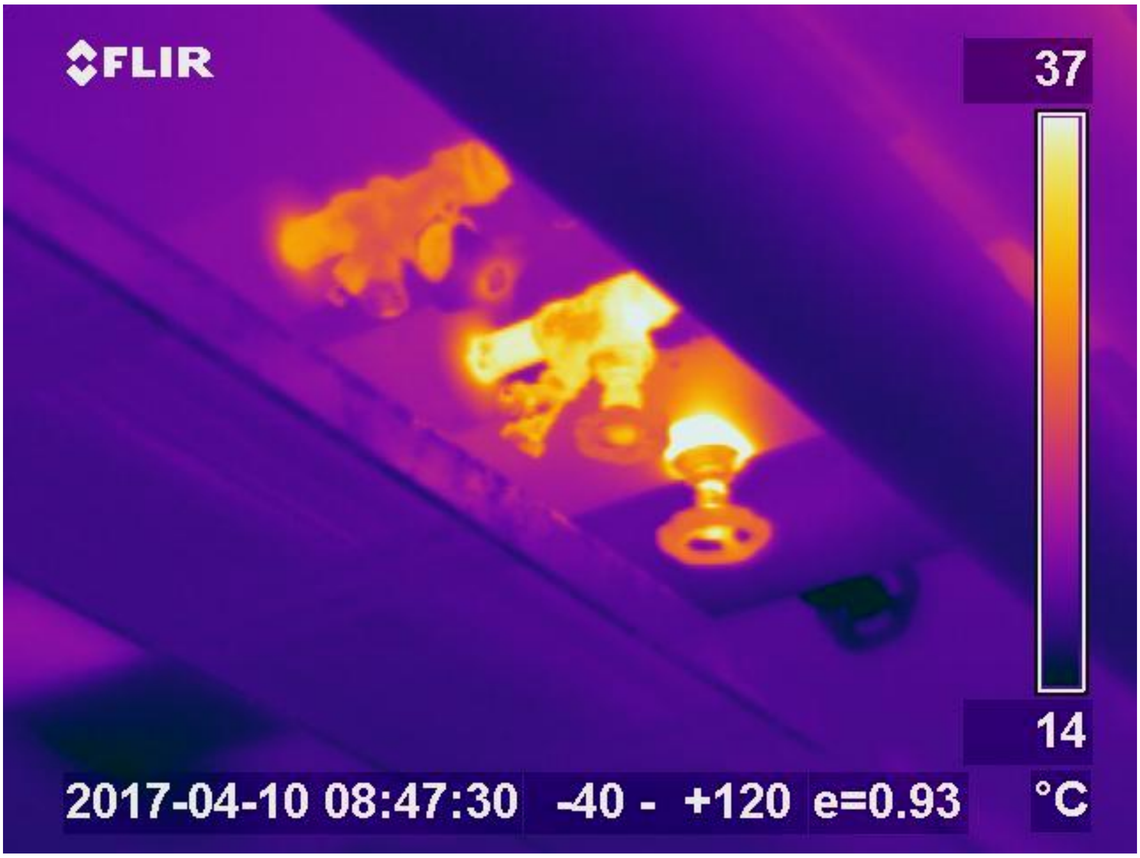


Figure 8.22: IR image (pipes)

Figure 8.23: IR image (facade)

Appendix C – IDA ICE

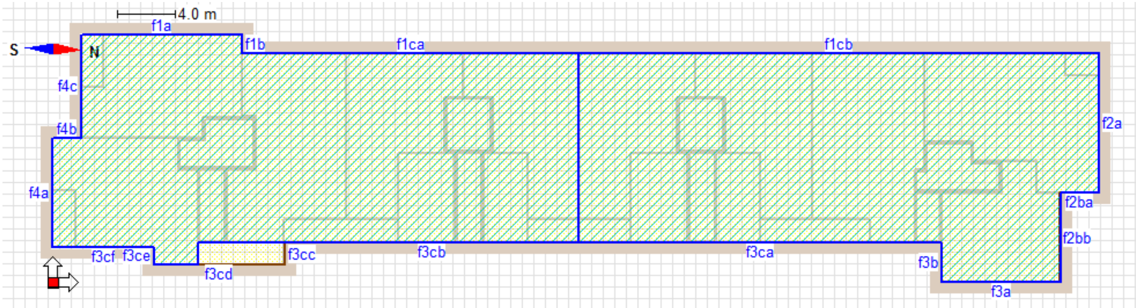


Figure 8.24: Floorplan basement

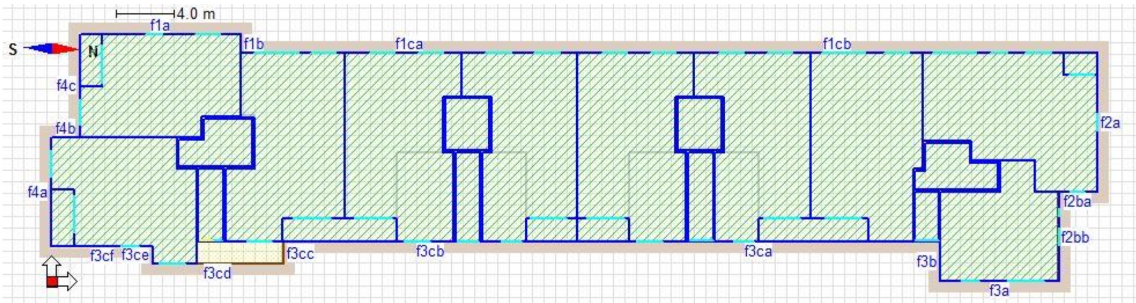


Figure 8.25: Floorplan apartments

Figure 8.26: 3D front view

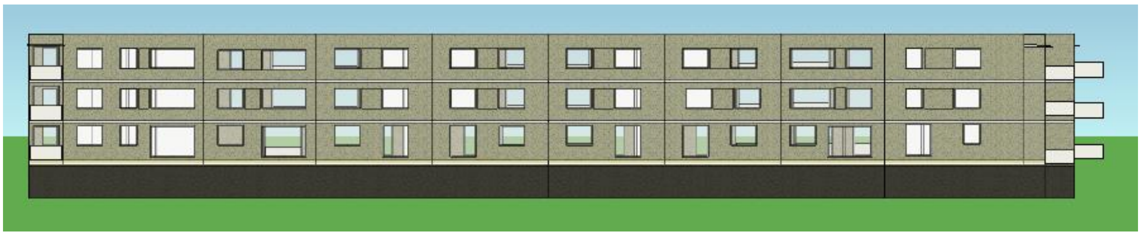


Figure 8.27: 3D back view

Input values

Table 17: Construction materials

Materials	Thermal conductivity [W/m K]	Density [kg/m3]	Specific heat [J/kg K]
Render	0.8	1800	790
Aerated concrete	0.15	500	1710
L/W concrete	0.15	500	1050
Concrete	1.7	2300	880
Wood roof	0.8	500	2300
Light insulation	0.036	20	750
Wood	0.14	500	2300
Hollow core block	0.6	1400	880
Wood wool	0.075	250	950

Table 18: Wall constructions and U-values

Construction	Material	Thickness [m]	U value [W/m2 K]
External wall	render	0.015	0.3739
	Aerated concrete	0.37	
	Render	0.015	
Internal wall	L/W concrete	0.1	1.195
Internal ceiling	Concrete	0.175	3.664
Roof	Wood roof	0.2	0.1127
	Light insulation	0.3	
	Concrete	0.2	
External slab	Concrete	0.05	0.3385
	Aerated concrete	0.4	
	Concrete	0.15	

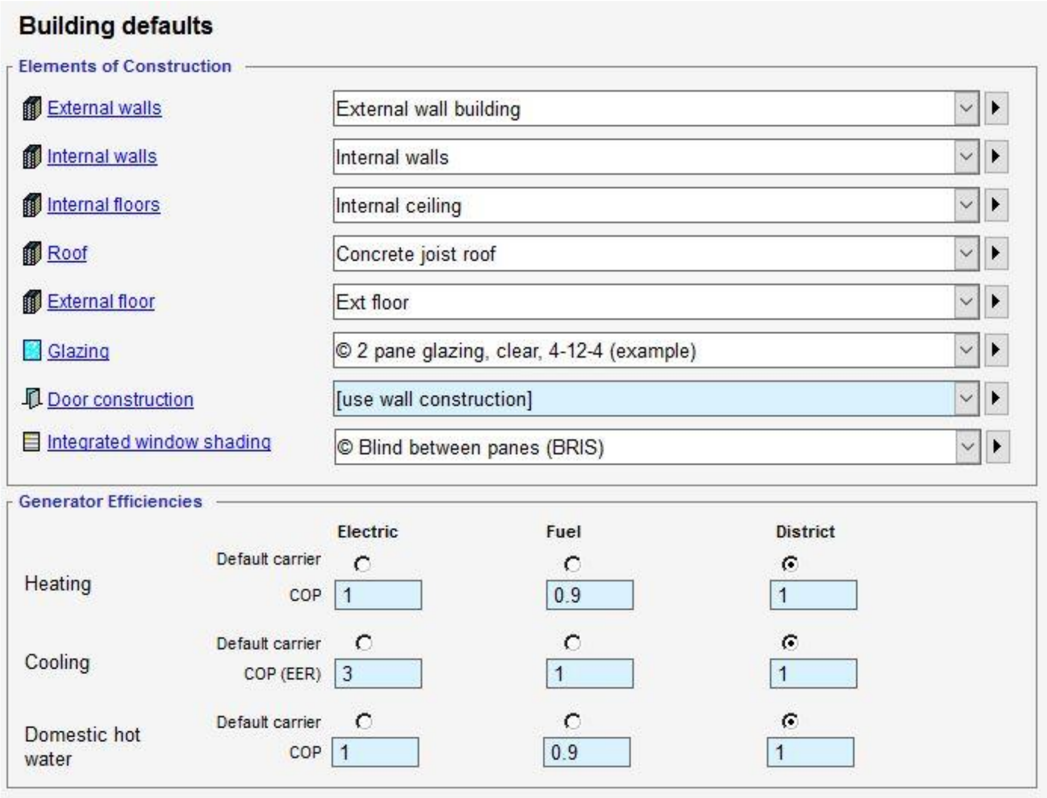


Figure 8.28: Default values for elements of construction and generator efficiencies, IDA ICE

Input data Report

Building	
Model floor area	3694.9 m^2
Model volume	9886.3 m^3
Model ground area	965.0 m^2
Model envelope area	3896.1 m^2
Window/Envelope	11.4 %
Average U-value	0.6757 W/(m^2 K)
Envelope area per Volume	0.3941 m^2/m^3

Figure 8.29: Input data Report overall data, IDA ICE

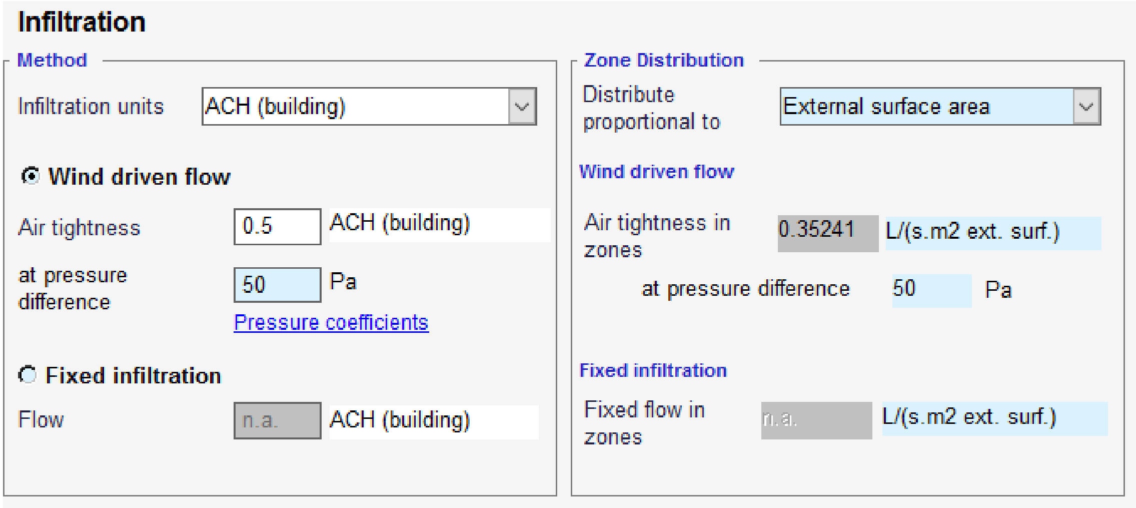


Figure 8.30: Infiltration, IDA ICE

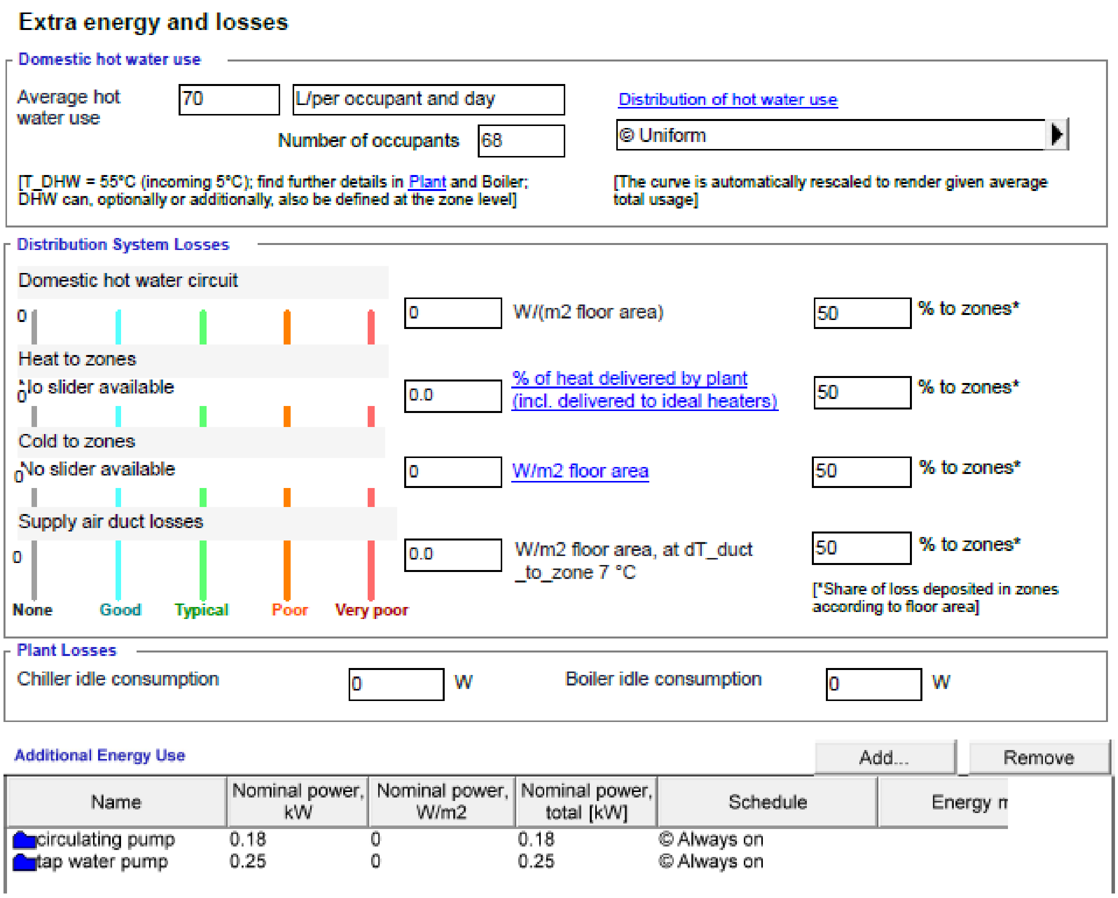


Figure 8.31: Extra energy and losses, IDA ICE

45-C0: a zone in Lierni_thesis_model (Loads)

Name	Type	Number of units	Power, W	Activity level	Control	Schedule	Energy meter	Mean, W	Yearly total, kWh
Occupant 1	© Occupant	2		1.0		© House living (...			
home lights	home Light	5	30		Schedule	© House lighting...	Lighting, tenant	62.501	547.5
cooker	cooker1	1	540			cooking	[Default] Equipment, tenant	45.0	394.2
laptop	laptop1	1	150			computer	[Default] Equipment, tenant	31.25	273.75
others	accessories	1	30.64			accessory	[Default] Equipment, tenant	30.64	268.41
tv	TV1	1	150			tele	[Default] Equipment, tenant	17.187	150.56
fridge-freezer	fridge-freezer1	1	82			© Always on	[Default] Equipment, tenant	82	718.32

Figure 8.32: Internal gains for apartments, IDA ICE

Basement warm: a zone in final_model_changed (Loads)

Name	Type	Number of units	Power, W	Activity level	Control	Schedule	Energy meter	Mean, W	Yearly total, kWh
washing m.(W...	© Equipment	1	2800			washing machine	Equipment, facility	291.68	2555.1
Light(9W+13W)	© Light	5	22		Schedule	© House lighting...	[Default] Lighting, facility	45.834	401.5
Light(9W+9W)	© Light	6	18		Schedule	© House lighting...	[Default] Lighting, facility	45.0	394.2
Light Laundry ...	© Light	7	72		Schedule	© House lighting...	[Default] Lighting, facility	210.0	1839.6
washing m. (...	© Equipment	1	1900			washing machine	Equipment, facility	197.92	1733.8
dryer	© Equipment	1	6000			dryer	Equipment, facility	874.98	7664.8
cold_ironer	© Equipment	1	200			cold ironer	Equipment, facility	4.1666	36.499

Figure 8.33: Internal gains basement warm, IDA ICE

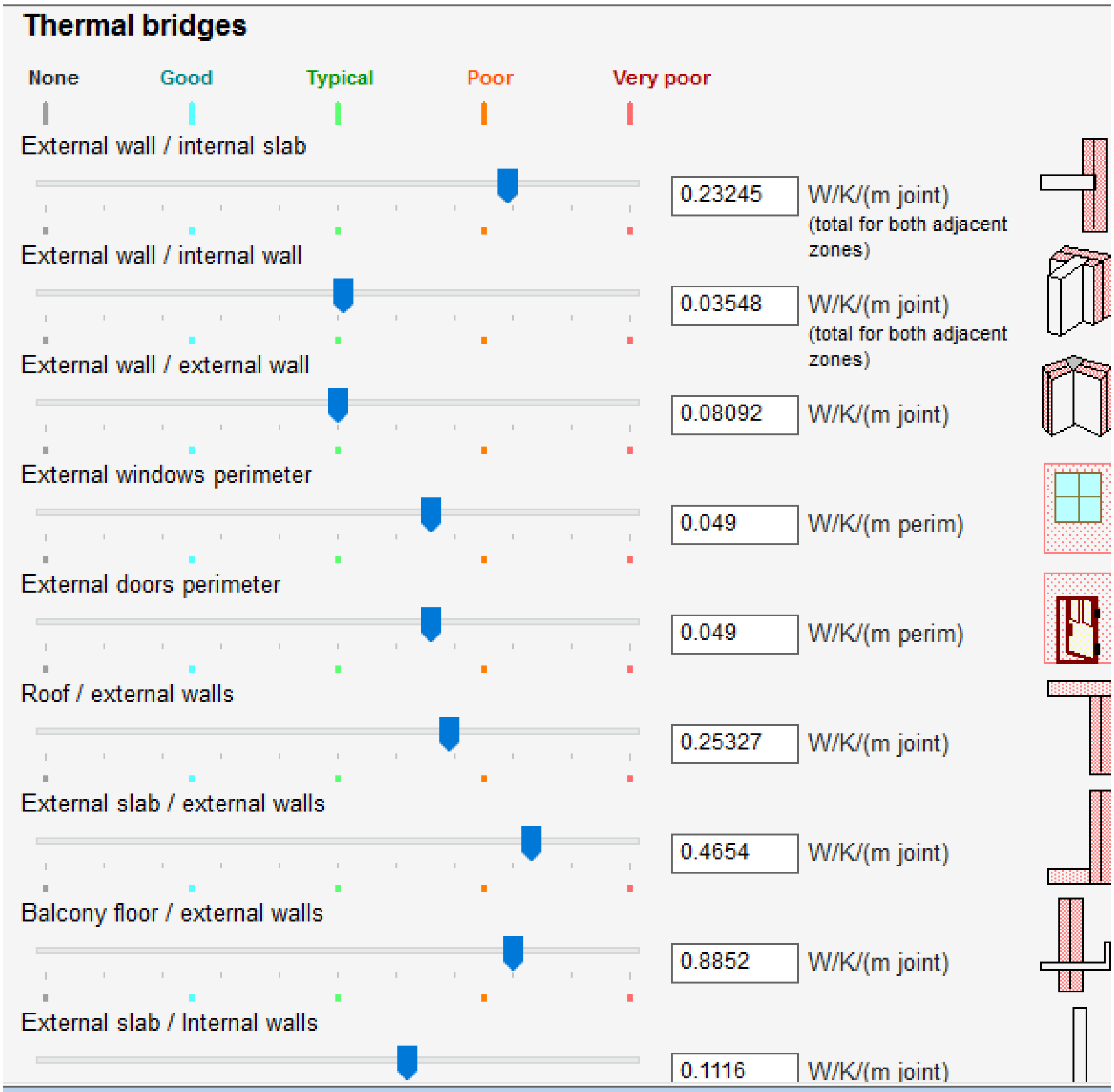


Figure 8.34: Thermal bridges, IDA ICE

Outputs

Building

Systems energy

	kWh
Zone heating	258323.8
Zone cooling	0.0
AHU heating	0.0
AHU cooling	0.0
Dom. hot water	101310.0
Cooling	0.0
Heating	359600.0

Figure 8.35: Breaking-down of district heating energy consumption, IDA ICE

		Purchased energy		Peak demand
		kWh	kWh/m^2	kW
	Lighting, facility	9256	2.5	2.52
	Equipment, facility	12040	3.3	10.51
	HVAC aux	4061	1.1	0.46
	Total, Facility electric	25357	6.9	
	District cooling	0	0.0	0.0
	District heating	359630	97.3	138.4
	Total, Facility district	359630	97.3	
	Total	384987	104.2	
	Lighting, tenant	18717	5.1	5.1
	Equipment, tenant	61705	16.7	21.0
	Total, Tenant electric	80422	21.8	
	Grand total	465409	126.0	

Figure 8.36: Delivered Energy Overview, IDA ICE

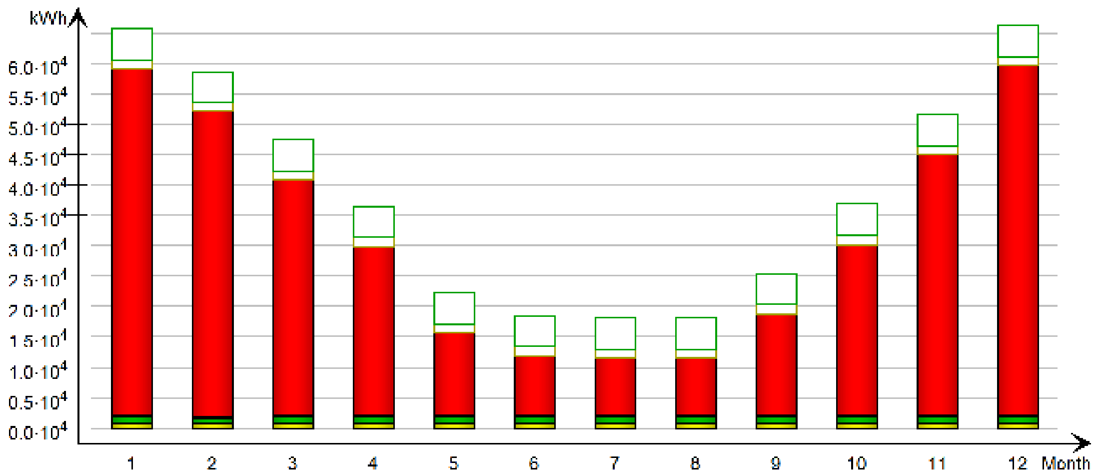


Figure 8.37: Purchased energy monthly, IDA ICE

kWh (sensible only)

Month	Envelope & Thermal bridges	Internal Walls and Masses	Window & Solar	Mech. supply air	Infiltration & Openings	Occupants	Equipment	Lighting	Local heating units	Local cooling units	Net losses
1	-22228.1	184.0	-21551.8	0.0	-16753.8	3490.2	6267.5	2369.9	48179.0	0.0	0.0
2	-20764.0	50.7	-17432.2	0.0	-15373.2	3201.4	5859.0	2217.5	42208.8	0.0	0.0
3	-18277.9	29.0	-10858.3	0.0	-12920.3	3407.5	6261.1	2373.5	29950.5	0.0	0.0
4	-15599.2	-183.2	-4466.0	0.0	-10913.1	3321.0	6049.3	2289.2	19462.5	0.0	0.0
5	-11748.1	-730.6	3433.7	0.0	-7715.5	3234.9	6241.7	2367.9	4885.0	0.0	0.0
6	-10283.5	-627.0	5277.5	0.0	-6766.0	2709.4	6030.4	2292.2	1346.9	0.0	0.0
7	-9622.8	499.1	4062.2	0.0	-6771.8	2504.6	6238.1	2375.0	673.8	0.0	0.0
8	-8848.9	763.8	2658.0	0.0	-6522.6	2700.3	6238.1	2377.5	598.0	0.0	0.0
9	-9994.6	514.8	-2855.1	0.0	-7546.7	3280.1	6024.3	2305.4	8255.0	0.0	0.0
10	-13212.3	201.1	-8548.3	0.0	-9914.4	3508.8	6237.7	2371.0	19332.6	0.0	0.0
11	-17285.9	175.3	-16126.9	0.0	-13025.9	3313.4	6039.0	2273.9	34598.8	0.0	0.0
12	-21954.6	82.5	-22281.2	0.0	-16793.0	3448.8	6258.3	2361.8	48835.6	0.0	0.0
Total	-179820.1	959.6	-88688.4	0.0	-131016.2	38120.2	73744.5	27974.8	258326.6	0.0	0.0
During heating (8784.0 h)	-152743.0	20812.7	-109709.9	0.0	-105090.6	27207.1	46117.7	14675.4	258284.4	0.0	0.0
During cooling (0.0 h)	-20835.9	-15821.0	17472.5	0.0	-21277.6	8825.3	22014.5	9633.7	0.0	0.0	0.0
Rest of time	-6241.2	-4032.1	3549.0	0.0	-4648.0	2087.8	5612.3	3665.7	42.2	0.0	0.0

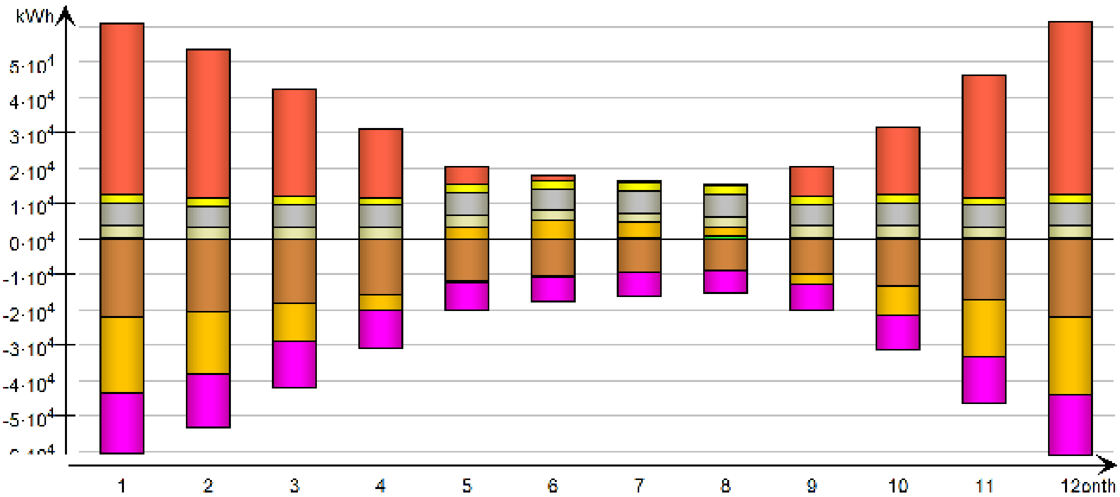


Figure 8.38: Energy balance table and chart whole building (sensible only), IDA ICE

Percentage of hours when operative temperature is above 27°C in worst zone	11 %
Percentage of hours when operative temperature is above 27°C in average zone	5 %
Percentage of total occupant hours with thermal dissatisfaction	12 %

Figure 8.39: Thermal comfort result, IDA ICE

Miele PROFESSIONAL

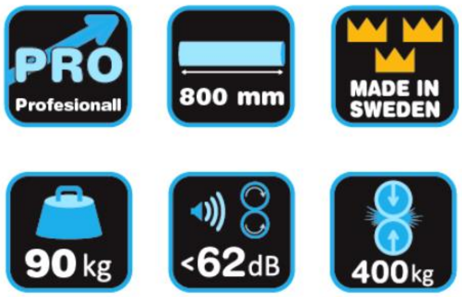
Kallmangel Pexymek KM 800
Användning i flerfamiljshus

Kallmangel KM 800

- Fastighetsmangel KM 800 är en energisnål och lättskött mangel av golvmodell.
- För maximal säkerhet är alla rörliga delar säkert inkapslade och försedda med fingerskydd.
- Mangeln är S-märkt och CE märkt
- Fastighetsmangel KM 800 har valsar av aluminium
- Valsbredd 800 mm bred, något som underlättar manglingen av breda lakan, påslakan, större dukar och liknande. Mangelgodset behöver helt enkelt inte vikas så många gånger.
- Anslutningskabel medlevereras

Teknisk data

Bredd	mm	1 085
Djup	mm	640
Höjd	mm	1070
Vikt	kg	70
Valslängd	mm	800
Valsdiameter	mm	108
Valstryck	max/kg	380
Mangeldukens längd	m	1,8
Elanslutning	V~	230
Anslutningseffekt	W	200



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Styrelsens säte: Solna

Vat-nr.: SE556138966801
Org.nr.: 556138-9668
Momsnr.: 01-556138-9968

Företaget har F-Skattebevis

Bankgiro: 644-4673
Postgiro : 661720-3
Bank : Skandinaviska Enskilda Banken

2016-02-23

Figure 8.40: Ironing machine datasheet

Produktfakta PT 7186 Vario

Kapacitet		
Trumvolym	l	180
Kapacitet (1:21)	kg	8.5
Kapacitet (1:20)	kg	9
Vattenförångning	l/h	8,1
Ljudnivå	dB(A)	<70
Material		
Patenterad skontrumma i rostfritt stål Kabinett pulverlackad, octoblå Manöverpanel, rostfritt stål		•
Elanslutning 3N AC 400V 50 Hz		
Anslutningseffekt	kW	8,5
Värmeeffekt	kW	7,94
Säkring	A	3 x 16
Radioavstörd		•
Ventilation		
Frånluftsanslutning	mm/ø	100
Max mottryck	Pa	420
Vid max mottryck/friblåsande	m^3/h	180/320
Förbrukningsvärden - bomull, skåpttort enligt EN61121, från 50% restfuktighet		
Torktid	min	39
Energi	kwh/kg tvätt	0,51
Tillval		
Gasuppvärmning		•
Vitt kabinett		•
Tillbehör		
Sockel öppen, höjd	mm	300
Luftmixdon		
XKM-RS 232-modul för dataförbindelse		

Figure 8.41: Dryer datasheet

Electrolux PROFESSIONAL LAUNDRY

Washer extractors
W465H

Features and benefits

- **Clarus Control' with:**
  - Fully programmable microprocessor
  - All relevant wash parameters can be programmed
  - Programming from key pad or downloading via memory card
- High extraction force for efficient dewatering
- Extremely low water and energy consumption – see table below
- Four compartment soap box for manual dosing of powder or liquid detergent
- Large door opening for easy loading/unloading
- Low noise level for pleasant working environment
- Stainless and galvanized steel in all vital parts for high degree of rust protection
- SuperBalance™ guarantees the correct extraction force

Images shown are a representation of the product only and variations may occur.

Main options

- Stainless steel front panel
- Stainless steel side panel
- Drain pump

Main specifications			**W465H**	
Max. capacity		kg/lb	7/15	
Drum, volume		litre	65	
diameter		ø mm	520	
Extraction		rpm	1100	
G-factor			350	
Heating alternatives, 230/400V	electricity	kW	2.0 / 3.0 / 5.4 / 7.5	
	steam		x	
	non-heated		x	
Consumption data "Normal 60°C" * (3G01)			El	Steam
Total time		min	45	**
Water consumption (cold+hot)		litre	43+11	43+11
Energy consumption (motor/heating)		kWh	0.15/0.3	0.15
Steam consumption		kg	-	0.5

* Water temperature 15°C cold water and 65°C hot water
** Depending on steam pressure

Certified in accordance with ISO 9001 and ISO 14001 and approved IP 24D.

Figure 8.42: Washing machine datasheet

Appendix D – Gantt Chart

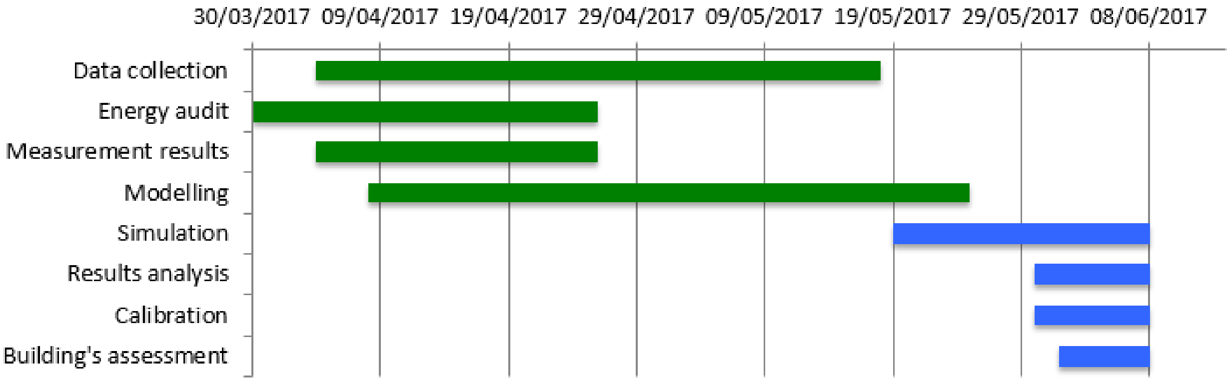

Figure 8.43: Gantt chart