Energy modelling of existing residential buildings and optimization of retrofitting strategies

Master's thesis in Building Technology

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CHALMERS UNIVERSITY OF TECHNOLOGY

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ABSTRACT

This project aims to create a simple yet accurate tool that can be used to:

1. Calculate the space heating demand , and,
2. Identify the optimal retrofitting scenario of an existing residential building in a time-efficient manner.

Climate change is one of the main challenges to overcome nowadays. Energy consumption in buildings, especially in dwellings, makes a significant contribution to this problem, emitting a considerable amount of greenhouse effect gases. One way with a high potential to reduce these emissions is making already existing buildings more energy efficient by retrofitting them. However, money is a substantial limitation to implementing retrofitting strategies, as renovation projects are costly. Therefore, cost-efficient retrofit measures should be found.

In this context, several studies are proposing different ways of achieving an optimal retrofitting strategy. Some of them are based in databases of measures that are combined optimallyy. Others more studies use more accurate methods for simulating the energy usage when different retrofit measures are involved, but rely on very time-consuming optimization strategies such as the genetic algorithm.

This Master Thesis aims to find a time-efficient tool that is able to simulate specific buildings and takes into consideration the effect of retrofitting different parts of the building envelope accurately, not relying on databases, but on actual simulations.

The energy modelling will be based on ISO 52016:1-2017 and developed in Matlab. The model will be validated with well-known commercial software. Using the capabilities of Matlab and considering the original goal regarding time-efficiency, non-linear optimization will be performed. This optimization strategy presents some limitations regarding the data input since cost functions are created from available commercial data, and the search for a local minimum, instead of using time-consuming global optimization tools.

After the energy model validation has been carried out and the optimization strategy selected, a case study based on a real building will be analyzed. From the case study, it can be observed that the tool gives coherent results in a reduced time.

Key words: energy, space heating, existing buildings, residential buildings, retrofitting, renovation, optimization.

Energy modelling of existing residential buildings and optimization of retrofitting strategies
Trabajo de Fin de Máster en el Máster en Ingeniería Industrial
JAVIER CASCO COMPANY

Escuela Técnica Superior de Ingenieros Industriales
Universidad Politécnica de Madrid

RESUMEN EJECUTIVO

Este proyecto tiene por objetivo crear una herramienta simple y precisa que se pueda emplear para lo siguiente:

1. Calcular la demanda de calefacción.
2. Identificar el escenario óptimo de renovación de un edificio residencial existente de una manera ágil.

El cambio climático es uno de los retos a abordar actualmente. El consumo de energía en edificios, especialmente residenciales, contribuye a empeorar este problema con la emisión de gases de efecto invernadero. Una manera con un amplio potencial es hacer que estos edificios sean más eficientes renovándolos con medidas que permitan consumir menos energía. Sin embargo, una limitación importante para implementación de estas medidas es el dinero, ya que estos proyectos son costosos. Por tanto, medidas de retrofit que sean eficientes económicamente deben ser propuestas.

En este contexto, existen diversos estudios que proponen diferentes maneras de conseguir una estrategia de renovación óptima. Algunas de ellas se basan en bases de datos de medidas que son combinadas de una manera óptima. Otros estudios utilizan métodos más precisos para simular el uso energético cuando se presentan diferentes medidas de renovación, pero se basan en algoritmos de optimización que necesitan una gran cantidad de tiempo.

Este Trabajo de Fin de Máster pretende establecer una herramienta ágil que sea capaz de simular el consumo de calefacción de edificios existentes y que tenga en cuenta el efecto de renovar diferentes partes de la cubierta del edificio de una manera detallada a partir de simulaciones, y no a partir de bases de datos.

El modelado energético se basa en la norma ISO 52016-1:2017 y se desarrolla en Matlab. El modelo se valida con un conocido software comercial de simulación de demanda de calefacción. Utilizando las capacidades de Matlab y teniendo en cuenta los objetivos de este trabajo relacionados con la agilidad de la herramienta, se utilizará optimización no-linear.Esta estrategia de optimización presenta algunas limitaciones en la entrada de datos, dado que se crean funciones de coste a partir de datos discretos. Asimismo, se trata de una estrategia de búsqueda de mínimos locales, en vez de mínimo global.

Tras la validación del modelo y la selección del método de optimización, se analiza un caso de estudio basado en un edificio real. Del caso de estudio se puede observar que la herramienta proporciona resultados satisfactorios.

Palabras clave: energía, calefacción, edificios existentes, edificios residenciales, retrofitting, renovación, optimización.

CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

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I would like to use this page for appreciating some people that have been really important for me personally and in this long journey that my higher education has been. Luckily, this journey does not end here, as there are always new things to learn and more wisdom to acquire.

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Gothenburg, 2018

Javier Casco Company

NOMENCLATURE

$A_{element}$	area of the building element, in m^2
A_k	area of the building element *k*, in m^2
A_{use}	useful floor area of the zone, in m^2
A_{tot}	sum of areas of all the building elements in the thermal zone, in m^2
a_{sol}	solar absorption coefficient at the external surface
B	geometric factor calculated as follows: $B = A_{floor}/(0.5 \cdot Perimeter_{floor})$
C_i	thermal capacity of the node *i*, in J/(kg·K)
C_{int}	thermal capacity of the internal environment of the zone, in J/K
c_a	specific heat of air at constant pressure $c_a = 1006$ J/(kg·K)
d_{bw}	total equivalent thickness for the basement walls, in m
d_{floor}	total equivalent thickness, in m
d_{layer}	thickness of a layer that composes the building element *k*, in m
d_{walls}	thickness of the walls that are in contact with the floor element, in m
$F_{appliances}$	usage factor of the appliances in the building
F_{fr}	frame area fraction of windows
$F_{occupants}$	occupation factor of the building
F_{sh}	shading reduction factor of external objects
F_{sky}	view factor to the sky from the element
F_w	correction factor for non-scattering glazing
f_{int}	convection factor of the internal gains
f_H	convection factor of the heating system
f_{sol}	convection factor of the solar radiation
g_k	total energy transmittance of the glazing of the element *k*, also called solar heat gain coefficient or *g*-value
$g_{normal;k}$	total energy transmittance of the glazing of the element *k* when the radiation impinges perpendicularly on the glazing
$H_{i;i+1}$	conductance between the nodes *i* and *i*+1, in W/K
H_{vent}	overall heat transfer coefficient for ventilation, in W/K
$h_{int\ conv}$	internal convective surface heat transfer coefficient, in W/(m^2·K)
$h_{int\ rad}$	internal radiative surface heat transfer coefficient, in W/(m^2·K)
$h_{ext\ conv}$	external convective surface heat transfer coefficient, in W/(m^2·K)
$h_{ext\ rad}$	external radiative surface heat transfer coefficient, in W/(m^2·K)
h_{n-1}	conductance between the node *n-1* and *n*, in W/(m^2·K)

I_{dif}	diffuse part (including circumsolar) of the solar irradiance, considering the position of the sun and the orientation of the building, in W/m^2
I_{dir}	direct part (excluding circumsolar) of the solar irradiance, considering the position of the sun and the orientation of the building, in W/m^2
Q_H	total energy demand in a year, in kWh
$q_{appliances}$	internal heat gain per square meter due to appliances, in W/m^2
$q_{occupants}$	internal heat gain per square meter due to occupants, in W/m^2
q_V	is air flow rate, in m^3/s
R_{bw}	thermal resistance of the wall basement, not including the effect of the ground, in (m^2·K)/W
R_{floor}	thermal resistance of the floor slab, in (m^2·K)/W
R_{ground}	thermal resistance of 05 m of ground, in (m^2·K)/W
R_{layer}	thermal transmittance of a layer that composes a building element, in m^2·K/W
R_{si}	thermal resistance of the internal surface, (m^2·K)/W
R_{se}	thermal resistance of the external surface, (m^2·K)/W
s_k	solar shading factor for the glazed element k
U_k	thermal transmittance of the element - also known as U-value - in W/(m^2·K)
z	depth of the basement floor below ground level (not including the floor insulation), in m
α_S	solar height, in º
β	inclination of a surface from a horizontal plane, in º
γ	angle between the projection of the normal to a surface in the horizontal plane and the north, clockwise, in º
γ_S	solar azimuth, in º
Δt	size of the time step, in s
$\Delta\theta_{sky}$	average difference between the apparent sky temperature and the air temperature, in ºC
θ	irradiance angle of the sun beams to a glazed element, in º
θ_{air}	internal air temperature, in ºC
θ_{ext}	external temperature, in ºC
θ_i	temperature of the node *i*, in ºC
$\theta_{mean\ radiant}$	mean radiant temperature, in ºC
θ_n	temperature of the node *n* of building element *k*, in ºC
$\theta_{n,j}$	temperature of the node *n* of building element *j*, in ºC
$\theta_{operative}$	operative temperature, in ºC
$\theta_{setpoint}$	temperature of the heating setpoint, in ºC
$\theta_{surf\ k}$	internal surface temperature of the building element *k*, in ºC

θ_{supply}	ventilation supply temperature of the zone, in ºC
θ_{upper}	operative temperature calculated when the maximum available heating is applied, in ºC
θ_0	free floating operative temperature, in ºC
κ_{ground}	areal heat capacity of the fixed ground element for a 0.5 m thick ground layer, in J/(m^2·K)
κ_{int}	thermal capacity of air and furniture $\kappa_{int} = 10\ 000\ \mathrm{J/(m^2 \cdot K)}$
κ_n	areal heat capacity of the node n, in J/(m^2·K)
λ_{ground}	thermal conductivity of the ground, in W/(m·K)
λ_{layer}	thermal conductivity of a layer that composes a building element, in W/(m·K)
ρ_a	air density at 20 ºC $\rho_a = 1.204\ kg/m^3$
$\Phi_{available}$	available heating or cooling load, in W
Φ_C	cooling load of the zone, in W
Φ_H	heating load of the zone, in W
Φ_{HC}	heating or cooling load of the zone, in W
Φ_i	sum of the different heat gains, in W
Φ_{int}	sum of the internal heat gains of the zone, in W
Φ_{sky}	thermal radiation to the sky, in W/m^2
Φ_{sol}	sum of the solar heat gains through transparent building elements (glazed elements) to the zone, in W
$\Phi_{unrestricted}$	unrestricted heating load, in W

SUBSCRIPTS

bf	refers to the element basement floor
bw	refers to the elements basement walls
k	refers to a building element k
n	refers to a node n
i	refers to a node i
t	refers to the time step t

1. Introduction

Climate change is one of the most significant challenges for the future of humankind. Currently, the average temperature of our planet has risen above one degree Celsius comparing to the pre-industrial age. The ice mass in the oceans has diminished substantially, CO_2 levels are rapidly increasing and disasters related to extreme weather are becoming usual [1]. The effects of climate change are unfortunately already noticeable, and its consequences are harming large amounts of people, habitats and the planet as a whole. Taking this into account, extraordinary efforts need to be put in order to mitigate the effect of this change if there is a will to keep the planet within sustainable limits.

In order to reduce the effect of climate change and ensure the sustainability of the planet, the United Nations dedicates one of its 17 Sustainable Development Goals to address this topic. More specifically, this goal, which holds the number 13, encourages "to take urgent action to combat climate change and its impacts".

The Paris Agreement [2] can be considered the official agreement that included more specific targets for the aforementioned goal 13. To this day, the agreement has already been ratified by 174 countries worldwide, acknowledges the emission of greenhouse gases (GHG) and the rise on its concentration in the air as a major cause of Climate Change. This agreement, which was enforced in 2016, pushed a common agenda in the participating countries in order to maintain a maximum global temperature rise and limit the emissions of GHG.

It can be said then, that mitigating climate change, and thus limiting the emission of GHG is a common goal for the humanity.

More specifically, in the European Union, when it comes to strategic planning concerning energy, there are well-defined targets. Specifically, by the year 2020, a reduction of 20 % in greenhouse gas emissions and an increase of 20 % in the share of renewable energies and energy efficiency, compared to the levels in the year 1990 [3]. For the year 2030, those figures are expected to be increased to 40 % and 27 %, respectively [4].

On longer-term planning, the so-called Energy Roadmap 2050, the European Union has the target of reducing by 80 % the GHG emissions and identifies renovation in existing buildings as a significant challenge in the road to achieve this goal [5].

When it comes to buildings, it should be considered that they account for 30 % of the CO_2 emitted to the atmosphere in relation to the energy consumption worldwide. The fuel usage causes about 6 % of the global emissions of this gas in residential buildings [6]. Moreover, the energy demand for heating and cooling in households is estimated to have a growth of approximately 80 % from 2010 to 2050 [7].

Narrowing down the scope to residential buildings, according to the latest energy balance provided by Eurostat [8], 25.71 % of the final energy consumption is made in the residential sector. Using the previous data, in Figure 1, a box-plot with the share of the final energy consumption in the residential sector in 38 different countries in Europe[1] is shown. It can be observed that the energy consumed by households takes a more than significant share nationwide.

It is interesting to showcase, as well, some examples outside of Europe. Argentina, 25 % of the consumed energy comes from residential buildings and these buildings often provide worse performance than the ones located in similar climatic regions in Europe [9].

[1] The countries included in this study are the EU-28 (including UK), Albania, Bosnia and Herzegovina, Iceland, Moldova, The former Yugoslav Republic of Macedonia, Norway, Serbia, Turkey, Ukraine and Kosovo.

In China, energy performance was not typically a relevant factor for the residential buildings erected before the publishing of the 'Guide for Developing Energy Efficiency in Residential and Public Buildings' in 2005 by the Ministry of Construction. This accounts for approximately half of the residential building stock. This is also a relevant fact in a country where 21.88 % of its energy consumption is related to residential buildings [10].

Going back to Europe and breaking down further the energy consumption in this sector, it can be found in Figure 2 that oil, solid fuels and gas, which have a remarkable carbon content, take slightly more than half of the consumed energy. As well, it needs to be taken into consideration the way in which the used electricity and derived heat are produced, which adds GHG emissions.

It is clear at this point that both reducing the amount of consumed energy and changing the energy sources are the paths to follow when tackling the reduction of GHG.

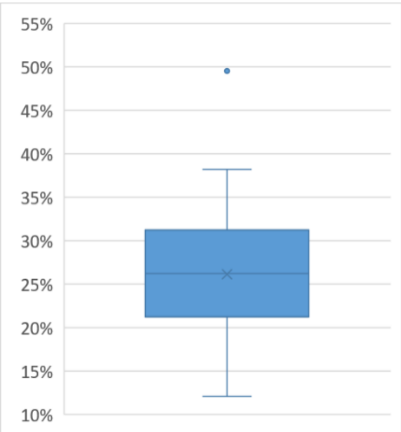


Figure 1. Percentage of final energy consumed by the residential sector in different European countries in 2016.

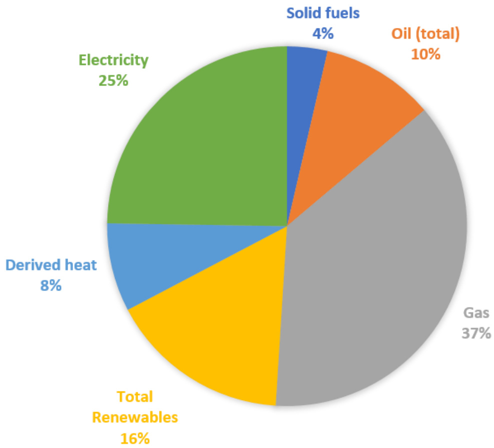


Figure 2. Final energy consumed by residential sector by type in Europe type in 2016.

An important aspect when it comes to analyzing the energy usage in buildings is its age. The year when the building was constructed has in most cases a direct connection with energy efficiency. It is due to mention that a big segment of the residential buildings in the European Union was built before any thermal regulation or standards were established. More specifically, as it can be observed from Table 1, a remarkable share of residential buildings was built before 1960. In addition, the majority of buildings were constructed before 1990, and these buildings have still a remarkable potential for energy consumption reduction.

From the data in Table 1, it can be quickly noticed that renovation and retrofitting of existing buildings has a remarkable potential in terms in reducing energy consumption, thus lowering the amount of greenhouse effect gases polluted into the atmosphere.

Nevertheless, in the following paragraphs more in-detail data will be provided for the case of Sweden, as this country is where the project will be based.

Table 1. Share of residential buildings according to the year they were built. Averaged data distributed by regions in the European Union. Elaborated with data from [11].

	South	**North & West**	**Central & East**
Before 1960	37 %	42 %	35 %
1961-1990	49 %	39 %	48 %
1991-2010	14 %	19 %	17 %

In 2014 in Sweden, the share of the final energy consumption due to space heating and hot water in one, two and multi-dwelling buildings was 15 % [12]. In total numbers, that is 55.3 TWh. Converting that to GHG emissions, the following figure can be calculated[2]: 1.39 million tons of CO2 equivalent.

In Sweden, as it can be observed in Table 2, the building stock in Sweden comprises a 77 % of dwellings that was constructed before the 1980s, which take more than 82 % of the energy consumption of the sector. Moreover, 91 % of the total number of residential buildings were built before the 2000s, which is when the first performance-based building code was introduced in the country. As it is shown in Table 3, the average energy consumption for space heating and water is notably higher before the 2000s.

Table 2. Swedish building stock in 2014. Data from Statistics Sweden [13] and Boverket [14].

	Total dwellings	**Percentage**	**Total energy use (TWh)**	**Percentage**
(…)-1940	900 948	20%	14,4	26%
1941-1960	933 779	21%	11	20%
1961-1970	867 584	19%	11	20%
1971-1980	723 346	16%	8,8	16%
1981-1990	406 050	9%	4,8	9%
1991-2000	222 834	5%	2,6	5%
2001-2010	216 710	5%	2,5	5%
2011- (…)	73 402	3%	0,2	0%
Data missing	19 842	1%	-	-
TOTAL	4 477 778	-	55,3	-

According to Dodoo et al. [15], the retrofitting measures applied to a multi-dwelling building built in 1972 can reduce the heat consumption from 34 to 53 %, and looking into the work of La Fleur et al. [16], the renovation of a building built in 1961 can achieve a drop of 44 % in the energy usage.

Taking into account the data from Table 3, if the energy consumption of the older buildings (built before 1980) is decreased until the levels shown in the *2011-(...)* interval by applying retrofitting measures, there is 433 kt of CO_2e that can potentially be avoided in the existing building stock. This energy reduction would be similar to the one mentioned in the studies above.

[2] Calculations made with data from the Swedish Energy Agency [12], Statistics Sweden [13] and CO2e conversion factors for fuels from Department for Business, Energy & Industrial Strategy from UK [62] for the year 2015.

Table 3. Average energy consumption per square meter for heating and hot water in 2014, by year of construction and building, in kWh/(m^2·year). Data from Boverket [14].

	Average energy consumption: One- or two-dwelling buildings kWh/(m2·year)	**Average energy consumption: Multi-dwelling buildings kWh/(m2·year)**
(…) -1940	125	146
1941-1960	116	144
1961-1970	106	134
1971-1980	90	135
1981-1990	96	118
1991-2000	95	120
2001-2010	82	106
2011- (…)	68	87

Making a comparison, such a reduction would be roughly the same as cutting the emissions of GHG from navigation, including recreational boats and large ships, railways, and mopeds and motorcycles in Sweden in 2016 [13].

Furthermore, if those buildings are to meet the Passive House Institute standards, which is 15 kWh/m^2 per year in space heating [17], it would mean a 71 % of energy consumption reduction in the whole residential building sector, or a saving potential of 1000 kt of CO_2e. Continuing with the comparison stated in the previous paragraph, this reduction would mean the same as cutting the emissions from the already stated means of transportation plus the domestic aviation in the whole country in 2016.

From the facts presented above, it can be concluded that there is a remarkable underlying potential in the renovation sector of existing buildings as it can contribute significantly to reduce the overall energy consumption and the emission of GHG emissions globally.

However, the effect of the measures taken to refurbish an existing building outside the operation time is often overlooked. Not only should the energy savings in the building within the operation time-frame be taken into account, but also the impact, the energy usage and the GHG emission of the product, construction and end-of-life stages.

In other words, a whole life cycle analysis should be performed in order to be certain of the overall greenhouse gases reduced in the renovation process. An appropriate indicator for this could be an energy return time. Nevertheless, this aspect, despite its importance, will not be covered by this project due to time limitations.

Another fundamental aspect to take into consideration in renovations is economic limitations. Fair use of monetary resources is central when approaching a renovation project, as this very reason might be the cause for not starting the project in the first place.

The majority of residential buildings in the European Union, specifically more than 80 %, are owned by private entities or individuals [11]. The only country in the union that has a larger share than 20 % of publicly owned residential buildings is Austria. This fact might be a cause that hinders the rate of renovations, as they involve a significant investment in the building with long payback periods, and private owners are usually not willing to spend their money under those circumstances.

It is due to mention as well, that private entities and individual owners do not always see the relevance of reducing the emissions of GHG or they simply ignore this fact as the emission is not directly seen through an exhaust pipe, as it might happen with the case of means of transportation. It is a common practice to start major renovation projects when the service life of the installed windows is finished. Thus, the motivation for starting renovation projects comes from a need, rather than an environmental or economic factor.

Due to this fact, it is critical to find optimal solutions in economic terms, as well as to raise awareness of the importance of reducing the emission of GHG, in order to encourage both private and public entities to invest in the renovation of existing buildings. This project will put a considerable emphasis on this aspect.

However, to have an order of magnitude of the payback periods, as a favorable argument to undergo major renovations, let us observe the data provided by Dodoo et al. [15] for the renovation of a residential block of 27 apartments constructed in the 1970s in Ronneby, in the south of Sweden. Considering the measures that involve insulation and window replacement on the "sustainability" package, which would reduce the space heating consumption by 38 %, the initial investment would be paid back in 24 years, which is less than half of the service life of the elements. This means that roughly half of the service years, the renovation will provide economic benefits.

1.1 Goal and scope of the project

The goal of this Master Thesis is creating a simple yet accurate energy simulation model and creating a detailed and time-efficient optimization tool for retrofitting the building envelope of existing residential buildings.

It is important to highlight that this study will focus on the demand side of buildings, especially in space heating. Local energy production falls out of the scope of this Master Thesis. Thus, the retrofitting options to be considered are insulation and window replacement.

This model, apart from simulating the building space heating demand, is expected to perform two different optimizations: the optimization of the budget for a target energy consumption reduction and the optimization of the retrofitting measures according to a given budget.

The motivation for the first optimization scenario lies on two pillars: the energy reduction plans encouraged by different organizations such as the European Union and the different building certifications that have a specific requirement of energy demand to be met. The second optimization is intended to help achieve the most energy savings in projects where the building owner has a budget limitation.

The tool aims to help decision-makers manage their budget with cost-effective measures in building renovations and provide support in the decisions in a planned renovation. For this reason, simple payback times in the optimization scenarios will be calculated.

Well-known commercial software will validate the created energy model. The tool and the simulations will be set in the region of Västra Götalands in Sweden.

2. Literature review

In the following sections, several topics will be presented in order to put into perspective the current state of the topic of this Master Thesis, both in a scientific and a commercial point of view.

Firstly, state-of-the-art research and software on retrofitting optimization will be presented. Afterward, the current energy consumption limitations for residential buildings in Sweden and the Passive House standard requirements will be explained. To conclude, a review of the relevant parts that need to be taken into consideration when modelling buildings and retrofit methods on those parts will be shown.

2.1 Current research and existing software for retrofitting optimization in existing buildings

Up to this day, there have been quite some studies on retrofitting measures to improve the energy consumption of existing buildings.

As an example, the work of Ma et al. [18] identifies the best retrofit options based on a generic scenario and reviews the current technologies available.

When it comes to optimizing the retrofitting strategies, different options in objective functions and approaches have been studied. Due to this diversity of options, Jafari and Valentin [19] proposed a decision matrix for selecting the function to optimize depending on the project, taking into consideration different stakeholders involved.

A usual approach towards the optimization of cost-effective energy retrofitting in buildings is based on building a database with different retrofitting measures. In this direction, several studies can be found, such as the one Kumbaroğlu and Madlener [20], which simulates the energy performance of buildings and creates a matrix with different measures, and Chidiac et al. [21], which apply regression analysis for simulating the energy saving potential in buildings through previously studied measures.

Other similar studies focus on multi-objective optimization. Wu et al. [22] developed a model using EnergyPlus for the simulation of the energy demands and CPLEX for optimizing. The aim of the model is optimizing both annual costs and GHG emissions. The model takes into account both retrofits in the building envelope as well as local production of energy with boilers, heat pumps, solar thermal and PV modules.

The optimization is posed as an epsilon-constrained mixed integer linear program and takes into consideration a set of previously simulated retrofit scenarios, along with the rest of the local energy production measures.

A lot of these methods take into account more aspects than space heating, such as appliances consumption and energy production. However, few of them have detailed simulation of the effects of retrofits and combinations of them.

Following a different strategy for optimization, some studies are using rather complex global optimization algorithms come to light. For example, Fan and Xia [23] built a retrofit model that takes a holistic view of the energy consumption of the building. According to their last paper [23], the optimization method is carried out with a genetic algorithm. With such a large number of variables, it takes a considerable amount of time to obtain an optimal solution.

Jafari and Valentin, in other of their studies [24], develop a decision-making procedure that involves detailed energy simulations and an optimization strategy that also involved the genetic algorithm. Like it was mentioned in the previous paragraph, this approach takes an important amount of time.

Regarding already available commercial software, it is due to mention the large variety of software on energy modelling in buildings, such as EnergyPlus, HAP and IDA ICE. All those options give excellent and detailed data about the energy consumption of the building. However, they not suitable for optimization of retrofitting strategies other than manual experimentation.

There is also some commercial software that involves application and optimization of retrofitting strategies.

As an example, there is the Passive House Planning Package (PHPP) developed by the Passive House Institute [25], which counts with a EnerPHit Retrofit Plan (ERP) and can compare different measures in a specific project. In the same line, there is EnExPlan [26] which calculates energy loads and gives suggestions on different retrofit options from a library.

These two tools have limited capabilities, as they rely on databases of retrofit options and do not offer detailed simulation on the interactions of the different measures in the studied building.

Lastly, the European project Dreeam [27], in which Chalmers University of Technology is involved, is developing an optimization tool for energy retrofit in residential buildings. This tool aims to provide optimal solutions for energy consumption and local energy production in residential buildings. However, this is still under development.

Given this context, this Master Thesis aims to provide a time-efficient optimization of the retrofitting measures for improving energy efficiency, while providing a reliable and detailed calculation of the space heating energy needs of a building using the hourly method provided by the newly released ISO 52016-1:2017 [28].

2.2 Current energy consumption limitations for residential buildings

In this section, the energy requirements for residential buildings in Sweden, specifically in the city of Göteborg will be depicted. The Swedish Building Regulation BBR 23, BFS 2016:6[3] [29], contemplates limits for yearly energy consumption for newly design buildings and existing buildings that undergo major alterations.

In Table 4 the aforementioned limits for the buildings in the climate zone IV, which includes the city of Göteborg, among others.

It is due to note that the specific energy use takes into account the energy for heating, comfort cooling, hot tap water and the building's property energy. This last one is related to the building needs for common spaces and does not include the occupants' use of energy and their appliances. As well, the energy is accounted per square meter of floor area that is intended to be heated to a temperature higher than 10 ºC.

[3] This regulation is not the latest one available. However, this one is used since it is the last one translated into English.

Table 4. Building's yearly specific energy use limit for residential buildings in the climatic zone IV in Sweden, according to BBR 23, BFS 2016:6.

Type of dwelling	Type of heating	Building's yearly specific energy use (kWh/m2)	Average U-value (W/m² K)
Single family house	Not electric	80	0.40
Single family house with heated area lower than 50 m²	Not electric	No requirement	0.33
Multi-dwelling blocks	Not electric	75	0.40
Multi-dwelling blocks with heated area larger than 50 m² and predominant heated area containing residential apartments smaller than 35 m²	Not electric	80	0.40
Single family house	Electric	50	0.40
Single family house with heated area lower than 50 m²	Electric	No requirement	0.33
Multi-dwelling blocks	Electric	45	0.40
Multi-dwelling blocks with heated area larger than 50 m² and predominant heated area containing residential apartments smaller than 35 m²	Electric	50	0.40

According to Sveby [30], a recommended input value for the energy used to produce hot tap water is 25 kWh/m² for block apartments and 20 kWh/m² for single-family houses.

According to the Swedish Building Regulation BBR 23, BFS 2016:6[4] [29], in case a building is renovated and does not comply with the requirements established for newly designed buildings, the renovation of the different parts of the building should aim for the U-values shown in Table 5.

Table 5. Target U-values for different building elements in renovations depicted in BBR 23, BFS 2016:6, in case the renovated building does not achieve the energy requirements for newly designed buildings.

Building element	Target U-value (W/m² K)
Roof	0.13
Wall	0.18
Floor	0.15
Window	1.2
Exterior door	1.2

Having specified the legal requirements for energy consumption in buildings in Sweden, it is relevant as well to mention the requirements for the EnerPHit certification developed by the Passive House Institute [25], which has a more ambitious goal in space heating demand.

[4] This regulation is not the latest one available. However, this one is used since it is the last one translated into English.

According to this standard, a residential building undergoing energy retrofits should have a maximum heating demand of 25 kWh/m^2 in a year in order to get this certification. This certification was created given that achieving the 15 kWh/m^2 required for the standard Passive House Certification was not entirely realistic for already existing buildings.

2.3 Retrofitting strategies

After setting the context of this project, a brief review of the state-of-the-art of the retrofit strategies for existing buildings, which will be considered in this project, will be discussed in this section.

It must be mentioned that these strategies are not the only ones, but they are the most suitable and cost-effective for existing residential buildings.

2.3.1 Building envelope insulation

One of the most noticeable parts of a building to examine when looking at the energy performance of it is the insulation of the building envelope. The walls, roof and floor take a large part of the building envelope and the contact area with the exterior, thus having correct insulation to avoid heat losses is very relevant.

In order to determine the thermal performance of a wall, it is necessary to know its thermal transmittance. This property, also called U-value, indicates the amount of heat that flows through the wall per unit of area due to a temperature gradient [31]. The lower the U-value, the least heat flow, and thus fewer heat losses through the walls.

U-values for walls can be measured on-site with a series of sensors, but they can also be calculated theoretically if the characteristics of the materials that comprise a wall are well known.

According to ISO 6946:2017 [32], a simplified method for calculating the U-value of a wall results from the inverse of the total thermal resistance. This last variable takes into account the contribution of all the materials that comprise the walls. The more materials with high thermal resistance, the more total thermal resistance. For the specific case of a wall made with homogeneous layers of materials, the total thermal resistance is the sum of the resistances of the different layers.

Furthermore, the thermal resistance of each homogeneous layer is calculated by dividing the thickness of the layer by the thermal conductivity of the material, as depicted in Equation (1).

$$R_{layer} = \frac{d_{layer}}{\lambda_{layer}} \qquad (1)$$

As it can be observed from the previous equation, thick layers and materials with low thermal conductivity make the thermal resistance increase, and therefore reduce the heat flow when there is a temperature difference in both ends of the wall.

Given that the thickness of the walls in buildings is a constraint due to a series of reasons – including material limitations, budget limitations and, all in all, practicality – it is preferred to add layers of materials with low thermal conductivity, i.e. insulating materials, to improve the overall thermal performance. Usually, these materials do not contribute to the structural integrity of the building, but they are mainly added due to its thermal performance.

When it comes to existing buildings, a common practice in order to reduce the heat losses through the walls is adding layers of insulation materials either in the external or in the internal wall. Both retrofitting measures have different procedures, with its benefits and drawbacks.

In terms of energy performance, according to the simulations made by Kossecka and Kosny [33], external insulation outperforms internal insulation by 2-11 %. This indicates that adding an external layer of insulation should be preferred according to this indicator. As well, the thermal bridges that there might appear in a wall are more likely to be covered by external insulation, as it is a more integral solution and covers the joints between floors.

Nevertheless, there are also other aspects that should be taken into consideration while deciding between adding an external or internal layer of insulation.

When it comes to the external façade, retrofit strategies might damage the aesthetics and the historical value of the building. Some areas, especially inner cities, have regulation restrictions in this regard that limit the number of options or even prevent this kind of measures to be performed.

Regarding the retrofit in the inner wall, issues like loss of useful space and the installation procedure, which prevents the usage of the house when adding the layers, might arise. By adding an additional insulation layer, the available residential space is reduced, which might come as a limitation and it definitely sets a boundary in the thickness of the insulation. However, the possibility to add an internal layer without construction works in the street makes it a more convenient and economical option.

Regarding the different insulation materials with which these retrofit measures can be done, a compilation of characteristics of traditional insulating materials can be observed in Table 6. The materials listed in this table have a common characteristic that makes them versatile, which is the ability to be adjusted on-site by being perforated and cut, while maintaining their insulation capacity.

According to a press release by IAL Consultants in 2015 [34], the insulation materials with the biggest market by volume of material are glass wool and stone wool, which comprise roughly 58 % of the total, followed by EPS, which represents 27.1%.

When it comes to emerging materials for building insulation, it is due to mention vacuum insulation panels (VIPs), aerogels, phase changing materials (PCMs) [35] [31]. The first two materials get thermal conductivities as low as 4 mW/(m·K). PCMs are not entirely considered insulating materials, as it will be explained later, however they help in regulating the interior temperature.

Vacuum insulation panels achieve to have such low thermal conductivity due to low-pressure gas or even absence of it inside a porous material [36]. However, they present some drawbacks apart from the high price, which are related to the inability to be cut or perforated for adjustment on-site without decreasing its thermal properties [35], which reduces its versatility notably. This insulation solution is already being commercialized by companies such as Porextherm Dämmstoffe GmbH [37].

Aerogels are very porous materials with very low thermal conductivities, and they are usually made of silica gels [36]. They are still expensive to produce, and the research is focused on lowering production costs for this material. However, this product is starting to be commercialized for building applications by companies like Svenska Aerogel [38].

Table 6. Characteristics of different traditional insulating materials. Data compiled from [35] and [31].

Insulation	**Material**	**Commercial format**	**Thermal conductivity (λ) [mW/(m·K)]**	**Additional information**
Glass wool	Borosilicate glass	Mats, boards and filling material	33-40	Good sound absorber, recyclable
Stone wool	Fibers of dolostone, basalt and diabase	Mats, boards and filling material	33-40	Recyclable
Expanded polystyrene (EPS)	Polystyrene	Boards	31-37	Easily flammable
Extruded polystyrene (XPS)	Polystyrene	Boards	30-40	Easily flammable
Phenolic foam	Phenolic compounds	Foam	18-28	Good reaction to fire
Polyurethane (PU)	Polyurethane	Panels, pipe sections and foam	22-40	-
Polyisocyanurate (PIR)	Polyisocyanurate	Foam	18-27	Higher fire resistance than PU
Cellulose	Recycled paper	Mats, boards and filling material	40-50	-
Cork	Cork	Panels and stripes	37-50	Good acoustic properties, easily recyclable

Phase changing materials help regulating the inner temperature of a building with a layer of material that has a melting point close to the comfort temperature. When the outside temperature increases, the PCM absorbs energy by changing its phase. Then, once the temperature decreases, the PCM solidifies again and, in this process, prevents the heat transfer towards the inside, as the change of phases is an isothermal process.

Another innovative solution with a great environmental potential are green roofs and facades. However, according to the study of Besir and Cuce [39], this solution is not suitable for cold climates, since the space heating saving potential is rather low.

2.3.2 Window replacement

Windows comprise a significant part of the building envelope and constitute a very important part of the building energy gains and losses. Not only do they have lower U-values comparing to the rest of the building envelope, but their transparency, and thus the effect of the solar heat gains, make windows one of the main factors to consider when studying the energy consumption in a building.

To show further how relevant windows are energy-wise in buildings, some studies assign more than 40 % of the energy losses in households to glazed areas [40] [41].

When approaching the energy analysis windows in a building, several aspects must be taken into account, such as the thermal transmittance (U-value), the solar heat gains through the glazing, shading strategies, the influence of air infiltration and the frame of the window. Nevertheless, some other aspects need to be assessed when designing a building, for instance, the visible transmittance.

There are several ways to assess the performance of windows, as it can be observed in [41]. The process used by the British Fenestration Rating Council (BFRC) results in an Energy Index (EI), which is a value presented in kWh/m^2/yr and accounts for the gained energy through the window. This index takes into account the all the aforementioned aspects in three variables: the U-value, the Solar Heat Gain Coefficient (SHGC) – also called g-value – and the air leakage (l_a) [42]. These variables are also usually the ones taken into account for windows when calculating the energy performance in buildings.

It must be considered that provided a g-value, it will usually be the one when the light has normal irradiance, i.e. when the light beam hits perpendicularly to the surface of the glazing. Windows have different g-values when the light reaches the surface on a different angle. The measure of this characteristic is somewhat complicated, and usually, empirical expressions are used. Schultz and Svendsen [43], propose the following formula:

$$g = g_o \left[1 - \tan^x\left(\frac{\theta}{2}\right)\right] \tag{2}$$

Where g_o is the g-value under normal irradiance, x is a correction factor that is usually close to 4 for most glazings [42] and θ is the irradiance angle.

According to the study carried out by Grynning et al. [41], the optimal combination of U-value and g-value for energy performance in an office building in Oslo are lower than 0.8 W/(m^2 K) and around 0.4, respectively.

In residential buildings, unlike offices or commercial ones, there is usually no cooling plants. Besides, there are less internal gains. Due to these reasons, the cooling load in households can be neglected [41]. Nevertheless, this data, especially the U-value, can be a relevant reference for the model that will be developed, as the studied building is located in the Scandinavian peninsula, which is the same region that will be used for this project.

Besides, Rezaei et al. [44] provides a set of suggestions for windows characteristics in different climates that is shown in Table 7, and it is, as well, a valid reference for choosing windows in renovations. It can be observed that the recommended g-value for cold climates is dissimilar to the one mentioned for the office building above. This is related to the end-use of the building: in office buildings, cooling loads are high, especially in Summer, and therefore a lower g-value is preferred to reduce the load. However, it must be said that this value can be altered through solar shading.

Table 7. Suggested windows characteristics for different environments.

Climate	**Visible transmittance**	**g-value**	**U-value (W/m^2 K)**
Cold climate	> 0.70	> 0.60	< 2
Temperate climate	> 0.70	> 0.50	< 2.5
Hot climate	> 0.60	< 0.40	< 4

In Sweden, the standard practice for retailers within the residential windows sector is providing the U-value. The usual U-values of the marketed windows varies from 0.7 W/K·m^2 for fixed (non-openable) windows to 1.5 W/K·m^2.

However, the *g*-value is usually not provided by the catalogues and brochures. In case simulations including this factor want to be performed, one must contact the window manufacturers and ask specifically for this value, or refer to the literature for standard values.

On the following lines, a review of the state-of-the-art technology for windows will be presented. On this review, two different structural parts of a window will be taken into account: the glazing and the frame.

2.3.2.1 Glazings

The glazing is the main part of the window and the one that has the most significant effect on the energy performance of the building. A standard classification for commercial glazings can be made considering the layers of glazing that it has. Therefore single, double, triple and even quadruple glazing can be found in the market. As the number of panes increases, the U-value and the *g*-value decrease and the price increases.

The ASHRAE® Handbook of Fundamentals [45] provides a comprehensive list of U-values and g-values for different kinds of glazing. In Table 8 it can be observed a summary of the mentioned properties of the glazing for different types of glazing. It is due to note that these values are shown for the simplest version of the glazings, and therefore they should be considered as an upper limit in the U-values for the mentioned type of glazing.

Table 8. Summary of U-values and g-values at 0º incidence of different types of glazings. Values at the centre of the glazing.[5]

Glazing	U-value $(\mathrm{W}/(\mathrm{m}^2 \cdot \mathrm{K}))$	*g*-value
Single glazing	5.91	0.86
Double glazing	3.12	0.76
Double glazing, low-e ($e = 0.2$ on surface 2)	2.56	0.65
Triple glazing	2.16	0.68
Triple glazing, low-e ($e = 0.2$ on surface 2)	1.87	0.60
Quadruple glazing ($e = 0.1$ on surfaces 2 or 3 and 4 or 5)	1.25	No data

Despite this data, the commercial windows that are currently available show more reduced U-values. As stated before, looking at the main window suppliers in Sweden, most of their offer comprises double and triple pane glazings with U-values from 0.7 to 1.5 W/(m^2·K).

Between the panes, there can be different glass fillings. The most usual are air and argon. According to the study by Arıcı and Kan [46], the usage of argon as a filling gas contributes to a decrease in the U-value of the window. This improvement in the insulation of the windows is relevant when the panes are made with low emissivity components. This is due to the dominance of radiation as the heat transfer mechanism in regular windows, and an increase in the relevance of conduction and convection when low emissivity materials are used.

[5] Note that there are many variants within the categories listed in this table. This table should only be taken as a reference and not as data to utilize in simulations.

According to Cuce and Rifat [42], krypton is also used as a filling glass. It offers better performance than argon in terms of insulation, although it is significantly more expensive. Taking a look at the current offer in the Swedish market, it is difficult to find this gas used for this purpose.

A conventional method to improve the thermal performance of windows is the use of low emissivity (low-e) coatings [44]. This extra layer applied to the glass allows the material to decrease the heat losses by reducing the emissivity of the glazing, thus diminishing the radiation of the glazing to the exterior of the building [47]. As well, low-e coatings provide a high transmittance in the visible range of the light spectrum, to allow light to penetrate the building, and high reflectance in the infrared, avoiding excessive heating in warm seasons.

It is due to mention as well some of the new technologies that are being developed in the window industry. However, they will not be explained in detail in this text, as these technologies are not widely commercialized or applied as retrofitting measures either because of technical issues or economic viability.

One of these innovative solutions for improving the performance of glazings is placing silica aerogel between panes. Due to its porosity, this material provides a high degree of insulation without compromising solar transmittance [42].

Windows that include Phase Changing Materials (PCM) increase the thermal storage capabilities of this building element. The filling between panes change its state – from solid to liquid or vice versa – according to the temperature, increasing the thermal inertia of the building and thus, smoothening the peak energy demand [44]. However, some problems like the volume change need to be addressed.

One interesting and promising solution for window retrofitting, especially in warm countries with a large number of hours of sun yearly, is photovoltaic glazing. These type of glazings would produce electricity that could be used for local consumption, reducing the energy need of the building.

Lastly, dynamic glazings must be mentioned. These glazings change characteristics within their use stage. They can be classified into passive and active systems. The first ones respond to external factors like light or temperature, whereas the latter respond to user-defined conditions. Active dynamic glazings are controlled through electricity [48]. These systems allow adapting the windows properties to provide the best thermal performance in every moment.

2.3.2.2 Frames

The frame of the window is the part that holds the glazing. It is a very relevant part of the whole window, as it can be a source of thermal bridges if the conductivity of the material is high. It is therefore essential to have frames made of materials with appropriate characteristics in order not to have thermal losses through this part of the building envelope.

Nowadays, the most typical materials for window framing are timber, aluminium and PVC. The ASHRAE® Handbook of Fundamentals [45] describes the characteristics of these materials for window frames in the following manner:

Timber has a low thermal transmittance and good structural properties, although its resistance towards the external climate is rather poor.

Aluminium is cheap and durable but has an inferior thermal performance due to its high conductivity. In order to increase the thermal resistance, thermal break are usually introduced, i.e., incorporating insulating materials to separate the part that is facing outside from the part that is facing indoors.

When it comes to PVC, it has a similar performance to timber both in terms of thermal performance and structurally. However, this material can be filled with insulation, since it is empty inside, thus increasing its thermal performance considerably.

A common practice for manufacturers is mixing these materials to get the best properties of each. As an example of this, companies like NorDan [49] or LEIAB fönster [50] offer aluminium coated timber frames.

Looking at the window frames that can be commercially found in Sweden, the most used materials are aluminium, wood and a mixture of both materials. The usage of PVC is for window frames is not as widely extended in the country as the materials above. As the window manufacturer NorDan states in its catalogue [49], the use of PVC in the Swedish climate is not maintenance free, and it is less sustainable as other options.

An aspect to consider as well, when it comes to the thermal performance of the whole window, is whether the frame allows the whole structure to be operable or not. The presence of sashes that allow operating the window increases the air leakages, thus offering a higher overall U-value. The cost of these operable windows is as well higher.

3. Energy modelling

The model for the simulation of energy consumption will be based on the method explained in the EN ISO 52016-1:2017 hourly calculations [28]. This method allows to obtain heating and cooling demands on buildings, as well as the operative temperature during a year. For this Master Thesis, the most relevant output of this calculation procedure is the heating demand.

The model will be applied to existing residential buildings which are expected to have poor energy performances. These buildings are usually constructed before the year 2000

A series of assumptions will be made for the model:

- Given that this type of residential buildings does not usually include air handling units, and the cooling loads in residential buildings in cold climates are small, they will not be taken into consideration.
- The building will be treated as a single thermal zone, as the whole building is intended to be heated to the same temperature.
- Since in residential buildings there are usually not Air Handling Units, the ventilation and infiltration flows are lumped together.
- The opaque building elements will be made of thermally homogeneous layers.
- The thermal bridges in the building envelope are not taken into consideration.

Note that the notation used in this project does not coincide with the one provided in the standard. The reason behind this decision is to ease the reading of the document and make it accessible to a non-expert.

The software that will be used for this project is MATLAB®. It is an engineering software that has its own programming language and several plotting and visualization options. It is especially useful for working with matrices and vectors. This software will be used due to its capacity to create personal programming code, easily solve linear systems of equations (by inverting matrices) and its optimization package. Besides, Microsoft® Excel® will also be used for quickly creating sheets for input data to the model.

3.1 About EN ISO 52016-1:2017

The EN ISO 52016-1:2017 has the status of European and Swedish standard and provides several approaches for calculating the energy demand for space heating and cooling, and the internal temperature of the building, as well as other calculations that will not be covered in this project.

It was approved as a Swedish standard on the 2nd of August of 2017 and it supersedes previous standards in the matter of energy needs in buildings, such as EN ISO 13791:2012 and EN ISO 13792:2012.

3.2 About the hourly method

The hourly method calculates the heating (and cooling) demand in the building throughout a year in an hourly basis, i.e., there will be a set of energy balance equations solved for every hour of the year.

For calculating this energy demand, the internal operative temperature needs to be solved first. This calculation takes into account the effects of the transient heat transfer between the exterior and interior of the building, through the various elements that comprise the building envelope. Note that the calculations do consider the effect of the thermal mass.

For the calculation of the internal temperature, different energy balance equations are solved: one on a thermal zone level and one per node of the building element. In this model, each opaque construction element (walls, roof, and floor) is divided into four layers and five nodes, whereas doors and windows are modelled just as one layer with two different nodes. As a convention, the nodes are numbered from outside to inside, being the first node the closest to the exterior, and the highest number the innermost node.

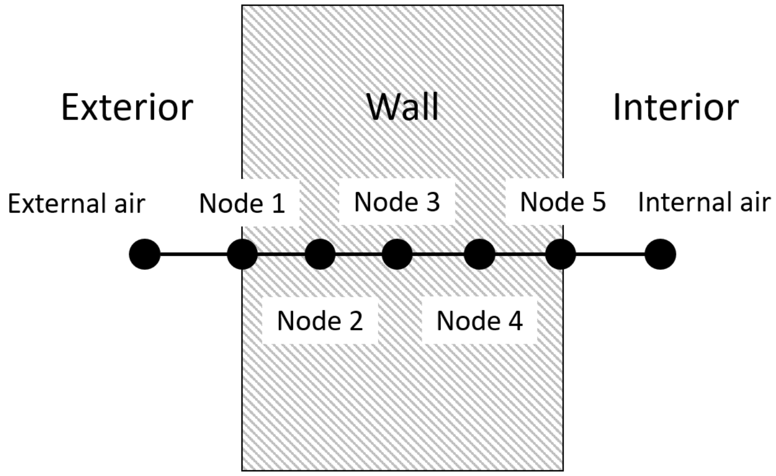


Figure 3. Node distribution in an opaque building element.

In a more detailed level, the thermal zone level balance equation takes into consideration the heat capacity of the air and furniture, ventilation, heat transfer between the air and the surfaces of the building elements, solar heat gains, internal gains and the necessary heating or cooling loads. The equation will be depicted further in the following sections.

When it comes to the building nodes, Figure 4 gives a comprehensive yet straightforward depiction of the processes that are involved in the different nodes of the building element energy balances.

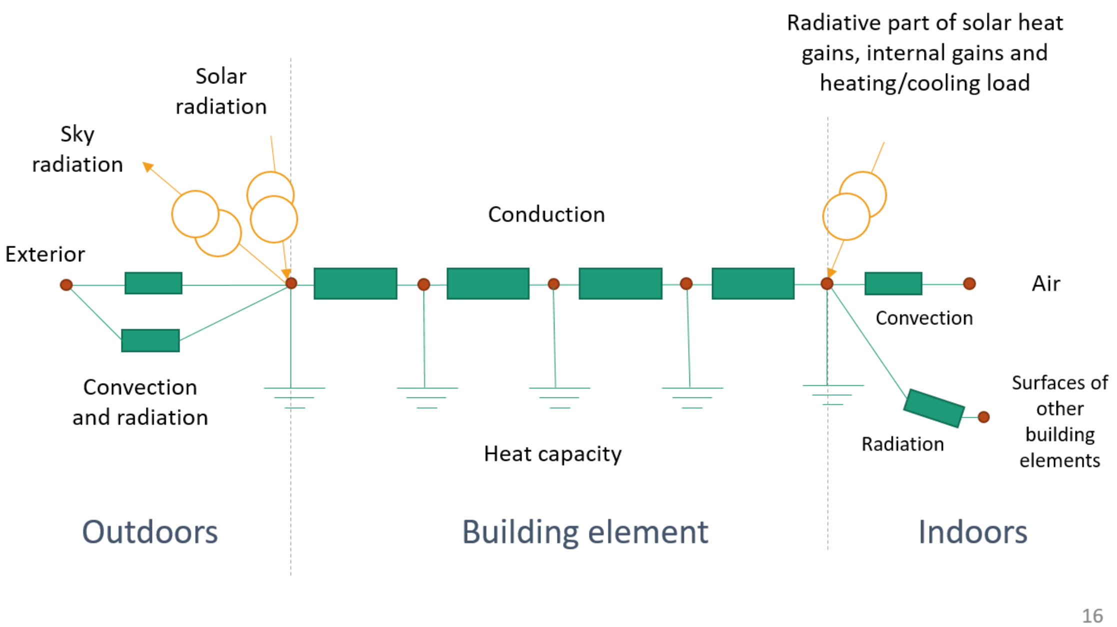


Figure 4. Equivalent RC model for the building element energy balances.

The internal operative temperature is calculated after solving the system of linear equations that results from the mentioned the energy balances.

3.2.1 Input and output data

3.2.1.1 Input data

The input data that must be provided to the model is:

- Climate data: hourly external air temperature and solar radiation in the different surfaces of the building in one year. Later, in this report, a simplified method for calculating the solar radiation in different surfaces from the impinging radiation on a horizontal surface will be explained.
- Building: dimensions, type of dwelling, ventilation rate, heating and cooling setpoints and internal gains.
- Building elements: U-values of the different building elements.
    - Opaque building elements: distribution of the thermal mass, estimation of the thermal mass of the element, absorptivity.
    - Glazed building elements: g-values and frame ratios.
- Ground properties: type of ground over which the building is built on.

3.2.1.2 Output data

The output of the model is the hourly space heating demand and cooling demand (if considered). According to the used ISO standard, the model also provides the hourly operative temperature.

3.3 Energy calculation procedure

The energy calculations aim to calculate the heating and cooling demand (sensible heating and cooling load) in the building throughout a whole year. In order to do that, the need for heating and cooling will be evaluated in an hourly basis depending on the internal operative temperature that is reached considering the temperatures in the previous hour and the external conditions. The hourly heating and cooling demand will be calculated in W and represented by Φ_H and Φ_C, respectively.

At the end of the year, all the hourly heating and cooling demands will be multiplied by the length of their time step and summed, to determine the total energy demand (Q_H) in kWh, as it is shown in Equation (3).

$$Q_{HC} = 0.001 \cdot \sum_t \left(\Phi_{HC;t} \cdot \Delta t\right) \tag{3}$$

For calculating the sensible heating or cooling load in a thermal zone in one-time interval, several steps should be taken. Firstly, a broad description of the steps will be made. Afterward, the detailed calculations will be shown. A flowchart of the simplified calculation process can be found in Figure 5.

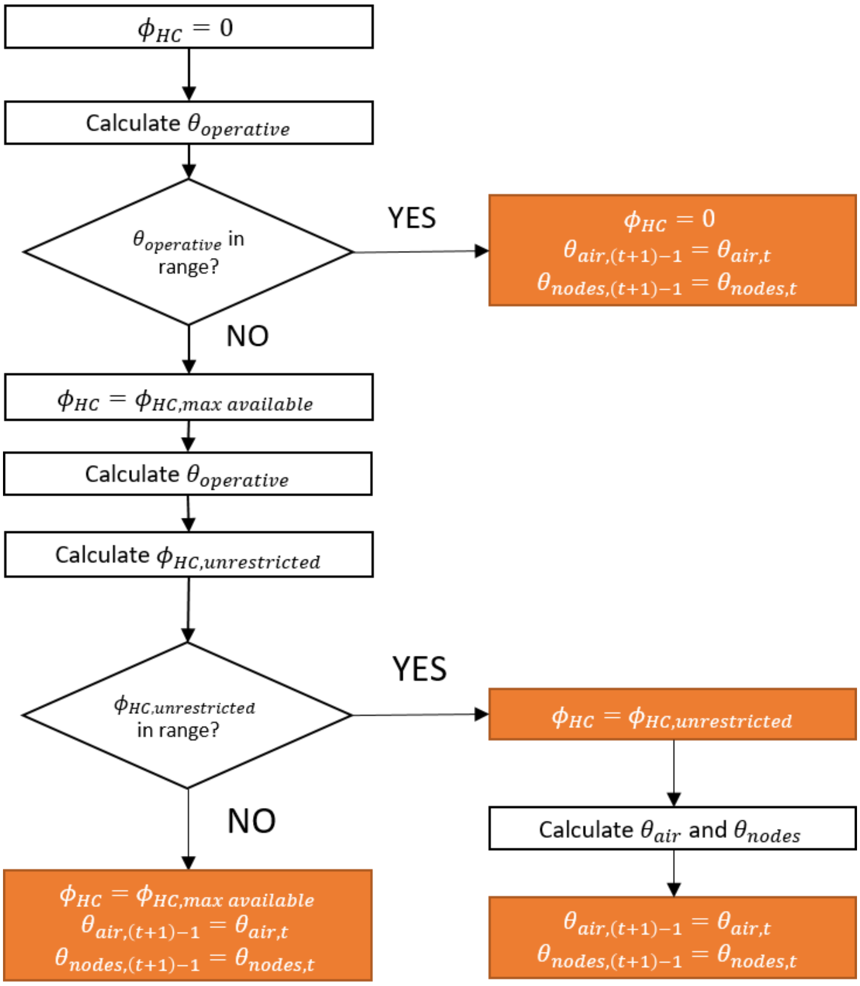


Figure 5. Simplified flow chart of the calculations for the sensible heating and cooling load for a thermal conditioned zone.

Firstly, the internal operative temperature should be calculated without any heating or cooling load. This operative temperature will be named *operating temperature in free-floating conditions* (θ_0). In case the operative temperature is higher than the setpoint for heating and lower than the setpoint for cooling, there will not be a need for either heating or cooling and the calculations for the next time step will start. Note that the temperatures of the air and all the nodes need to be stored for the following time step.

In case the operative temperature is lower than the heating setpoint, there will be a need for heating. The heating demand is now set to the maximum available heating power and the operative temperature is calculated again. This newly calculated operative temperature will be called *upper operative temperature* (θ_{upper}). With this temperature, the unrestricted heating load will be calculated with the following formula:

$$\Phi_{unrestricted} = \Phi_{available} \cdot \frac{(\theta_{setpoint} - \theta_0)}{(\theta_{upper} - \theta_0)} \tag{4}$$

It can be observed that Equation (4) is a linear interpolation.

Once the unrestricted heating load is calculated, the heating power available needs to be checked. In case the unrestricted heating demand is lower than the available power, the final heating load will be the unrestricted heating demand, and the actual operative temperature will be set to the setpoint. The air and nodes temperatures will be calculated again with this heating load and stored for the next time step.

In the event of having the unrestricted heating load higher than the available heating power, the final heating load will be set as the maximum available heating power and the temperatures for the following time step will be the ones previously calculated with the maximum available heating power. Note that in this case, the operative temperature does not reach the setpoint.

In case the operative temperature is higher than the cooling setpoint, the same process is carried out. The only difference with the case where there is a need for heating is the sign of the unrestricted load, which, in this case, is negative.

To summarize, there are five possible situations in every time step:

- The free-floating temperature is higher than the heating setpoint and lower than the cooling setpoint and there is no need for heating.
- The free-floating temperature is lower than the heating setpoint, i.e., there is a need for heating, and:
    - The required heating power is available, and the operative temperature reaches the setpoint.
    - The maximum available heating power is not enough to reach the setpoint.
- The free-floating temperature is higher than the cooling setpoint, i.e., there is a need for cooling, and:
    - The required cooling power is available, and the operative temperature reaches the setpoint.
    - The maximum available cooling power is not enough to reach the setpoint.

3.3.1 Calculation of the operative temperature and energy balances

The operative temperature is calculated as follows:

$$\theta_{operative} = \frac{\theta_{air} + \theta_{mean\ radiant}}{2} \tag{5}$$

where, θ_{air} is the internal air temperature and $\theta_{mean\ radiant}$ is the mean radiant temperature.

The mean radiant temperature is the weighted average of the internal surface temperature of all the building elements:

$$\theta_{mean\ radiant} = \frac{\sum_{elements}(\theta_{surf\ k} \cdot A_{element})}{\sum_{elements}(A_{element})} \tag{6}$$

Both the internal air temperature and the internal surface temperature of all the building elements are calculated by solving balance equations. As a matter of fact, the variables that need to be calculated to obtain the mean radiant temperature are not only the internal surface temperature, but the temperature in all the nodes of all building elements. Therefore, the energy balance equations will be solved in thermal zone level and node level.

The solving strategy consists on obtaining a system of linear equations with the usual $Ax = B$ form. In this case, A is a square matrix with the coefficients of the unknown temperatures, B is a vector with the source terms and boundary conditions, and x is the vector that contains the unknown temperatures. Once this form is obtained after some redistribution of the equations, the system can be easily solved by matrix inversion.

The primary energy balance equation that is solved in the model is based on the following expression:

$$\frac{C_i}{\Delta t} \cdot \left(\theta_{i;t} - \theta_{i;t-1}\right) = H_{i;i+1} \cdot \left(\theta_{i+1;t} - \theta_{i;t}\right) + \Phi_{i;t} \tag{7}$$

Note that this equation is the result of discretizing the one-dimensional unsteady heat conduction equation in an implicit form.

3.3.1.1 Energy balance: thermal zone level

On a thermal zone, the energy balance takes into account the heat transfer from the building elements surface and the internal air, thermal inertia as well as the ventilation. Besides, internal gains, solar gains and heating loads are also included.

$$\begin{aligned} \frac{C_{int}}{\Delta t} \cdot \left(\theta_{air;t} - \theta_{air;t-1}\right) + \sum_{k=1}^{elements} \left(A_k \cdot h_{int\ conv,k} \cdot \left(\theta_{air;t} - \theta_{surf\ k;t}\right)\right) \\ = H_{vent;t} \cdot \left(\theta_{supply;t} - \theta_{air;t}\right) + f_{int} \cdot \Phi_{int} + f_{sol} \cdot \Phi_{sol} + f_H \cdot \Phi_H \end{aligned} \tag{8}$$

The values for the convection factors can be obtained from the suggested values from Annex B of the used ISO standard [28]:

Table 9. Suggested values for the different convection factors.

Convection factor	Suggested value
f_{int}	0.40
f_{sol}	0.10
f_H	0.40

Rearranging the equation, the following expression is obtained:

$$\begin{aligned} &\left[\frac{C_{int}}{\Delta t} + \sum_{k=1}^{elements} \left(A_k \cdot h_{int\ conv,k}\right) + H_{vent;t} + H_{tb}\right] \cdot \theta_{air;t} \\ &- \sum_{k=1}^{elements} \left(A_k \cdot h_{int\ conv,k} \cdot \theta_{surf\ k;t}\right) \\ &= \frac{C_i}{\Delta t} \cdot \theta_{air;t-1} + H_{vent;t} \cdot \theta_{supply;t} + f_{int} \cdot \Phi_{int} + f_{sol} \cdot \Phi_{sol} + f_{HC} \cdot \Phi_{HC} \end{aligned} \tag{9}$$

The internal thermal capacity of the internal environment of the zone C_i is calculated according to:

$$C_{int} = \kappa_{int} \cdot A_{use} \tag{10}$$

where the thermal capacity of air and furniture has a value of $\kappa_i = 10\ 000\ \mathrm{J/(m^2 \cdot K)}$.

The useful floor area (A_{use}) includes the horizontal area in every level of the building, which is enclosed inside the building envelope and intended to be heated more than 10 ºC. This excludes load-bearing parts, voids and zones where the ceiling has a height lower than 1.5 m. The area occupied by non-load bearing walls and openings for stairs is included in this definition. In residential buildings, garages are not included [29] [51].

Conventional internal convective surface heat transfer coefficients ($h_{int\ conv}$) are given in EN ISO 13789:2017 [52], and are shown in Table 10.

Table 10. Conventional internal surface heat transfer coefficients, according to the direction of the heat flow.

Surface heat transfer coefficient (W/m²·K)	Upwards	Horizontal	Downwards
Internal convective surface coefficient, $h_{int\ conv}$	5.0	2.5	0.7

The ventilation heat transfer coefficient $H_{vent;t}$ is calculated in an hourly basis in the following way:

$$H_{vent;t} = \rho_a \cdot c_a \cdot q_{V;t} \tag{11}$$

NOTE: The Swedish building regulation BBR 23, BFS 2016:6 [29] classifies the minimum air flow rate for ventilation in two cases: empty and occupied. For the first case, the air flow rate is 0.10 l/s per m^2 of useful floor area, and for the second, 0.35 l/s per m^2 of useful floor area. According to ISO 17772-1:2017 [53], a standard input value for air flow rates for residential buildings is 0.5 l/s per m^2 of useful floor area.

The internal heat gains of the zone are calculated as follows:

$$\Phi_{int} = \left(q_{occupants} + q_{appliances}\right) \cdot A_{use} \tag{12}$$

In Equation (12), the gains produced by heating, cooling and ventilation systems, as well as the gains due to hot water, sewage systems, processes and goods are neglected, due to the nature of the assessed building. Besides, internal gains due to lightning are also neglected, according to ISO 17772-1:2017 [53], they should only be considered in non-residential buildings.

An informative set of values for these internal gains can be found in ISO 17772-1:2017 [53], which are shown in Table 11.

Table 11. Internal gains per square meter on residential buildings, by type of gain.

Internal gains (W/m²)	One-, two-dwelling apartments	Multi-dwelling apartments
Occupants	2.8	4.2
Appliances	2.4	3.0

To the aforementioned internal gains, a usage factor should be applied, since the building is not equally occupied throughout the day or during weekdays and weekends. These usage factors are suggested as well in ISO 17772-1:2017 [53], and shown in Appendix A. Therefore, the internal gains are calculated as:

$$\Phi_{int} = \left(F_{occupants}(t) \cdot q_{occupants} + F_{appliances}(t) \cdot q_{appliances}\right) \cdot A_{use} \tag{13}$$

The calculation of solar heat gains through glazed elements according to the standard is shown in Equation (14).

$$\Phi_{sol} = \sum_{k=1}^{glazings} \left[g_k \cdot \left(I_{dif;k} + I_{dir;k} \cdot F_{sh;k}\right) \cdot A_k \cdot \left(1 - F_{fr;k}\right)\right] \tag{14}$$

In order to simplify the model, the shading reduction factor of external objects, $F_{sh;k}$, will be considered as 1.

The frame area fraction of the element k is calculated with the ratio between the areas of the glazed part of the element and the whole element:

$$F_{fr;k} = 1 - \frac{A_{glazing;k}}{A_k} \tag{15}$$

The g-value is a property of the glazing and this value will be taken as input data. Nevertheless, given that the g-value is dependent on direct and diffuse irradiance, and in the angle of incidence, there is a need for a correction. The correction used is the one for non-scattering glazing and is provided in ISO 52016-1:2017.

$$g_k = F_w \cdot g_{normal;k} \tag{16}$$

This correction factor has a suggested value of 0.9.

Besides, if the case of shading devices wants to be taken into consideration, a shading factor s_k can be introduced in Equation (15). However, for simplicity, the windows will be considered to have no shading devices. This factor will be then introduced to the model, just in case there is a need for it in the future but set to 1.(17)

Taking all the above into consideration, the solar heat gains will be calculated with the formula depicted in Equation (17), with the aforementioned correction of g_k.

$$\Phi_{sol} = \sum_{k=1}^{glazings} \left[s_k \cdot g_k \cdot \left(I_{dif;k} + I_{dir;k} \right) \cdot A_k \cdot \left(1 - F_{fr;k} \right) \right] \tag{17}$$

3.3.1.2 Energy balance: building element level, internal surface node

In the building element level, there is a need for a distinction of the balance equation depending on the node where the energy balance is focused on. The following energy balances in the building element level: internal surface node, inside node and external surface node, must be applied to every building element in the construction.

In the internal surface node in a building element k, the energy balance will look like in Equation (18).

According to the numbering convention, these internal surface nodes will have the highest number, i.e., node 5 in opaque elements and node 2 in doors and windows. Therefore, in this equation: *n=5* for opaque elements and *n=2* for windows and doors.

Note that all the coefficients are referred to the building element k, excluding the ones which include the subscript j, which refer to the other building elements.

$$\begin{aligned} \frac{\kappa_n}{\Delta t} \cdot \left(\theta_{n;t} - \theta_{n;t-1} \right) & \\ = h_{n-1} \cdot \left(\theta_{n-1;t} - \theta_{n;t} \right) &+ h_{int\,conv} \cdot \left(\theta_{air;t} - \theta_{n;t} \right) \\ &+ \sum_{j=1}^{elements} \left(\frac{A_j}{A_{tot}} \cdot h_{int\,rad} \cdot \left(\theta_{n,j;t} - \theta_{n;t} \right) \right) \\ &+ \frac{1}{A_{tot}} \left[(1 - f_{int}) \cdot \Phi_{int} + (1 - f_{sol}) \cdot \Phi_{sol} + (1 - f_H) \cdot \Phi_H \right] \end{aligned} \tag{18}$$

Rearranging the terms of Equation (18):

$$-\left(h_{n-1}\cdot\theta_{n-1;t}\right)+\left[\frac{\kappa_n}{\Delta t}+h_{int\,conv}+h_{int\,rad}\cdot\sum_{\substack{j=1\\j\neq k}}^{elements}\left(\frac{A_j}{A_{tot}}\right)+h_{n-1}\right]\cdot\theta_{n;t}$$

$$-h_{int\,conv}\cdot\theta_{air;t}-\sum_{\substack{j=1\\j\neq k}}^{elements}\left(\frac{A_j}{A_{tot}}\cdot h_{int\,rad}\cdot\theta_{n,j;t}\right) \tag{19}$$

$$=\frac{\kappa_n}{\Delta t}\cdot\theta_{n;t-1}+\frac{1}{A_{tot}}\left[(1-f_{int})\cdot\Phi_{int}+(1-f_{sol})\cdot\Phi_{sol}+\ (1-f_H)\cdot\Phi_H\right]$$

For the calculation of the areal heat capacity κ_n, the class of the building element according to its distribution of mass needs to be considered. The process varies for opaque elements in contact with the external air, opaque elements in contact with the ground and glazed elements[6].

Selecting the correct mass distribution is essential, as it affects the thermal performance of the building element. There is a need to re-evaluate this in case a wall is modified by adding extra insulation, as the distribution of the thermal mass will most probably vary.

When it comes to windows, their thermal mass is neglected. Thus, in glazed elements: $\kappa_n = 0$.

As for opaque elements, excluding the ones in contact with the ground, each node has a different value depending on the distribution of the mass in the element. The different options provided in the standard follow a logical distribution of the areal heat capacity of the building element among the five nodes. These options and its respective κ_n values are:

- Mass concentrated at inthe ternal side: the insulation is located in the external part of the wall. The internal node gets the whole value of the areal heat capacity of the element.

$$\begin{gathered}\kappa_5=\kappa_m\\ \kappa_2=\kappa_3=\kappa_4=\kappa_5=0\end{gathered} \tag{20}$$

- Mass concentrated at outer side: the insulation is located in the internal part of the wall. The external node gets the whole value of the areal heat capacity of the element.

$$\begin{gathered}\kappa_1=\kappa_m\\ \kappa_1=\kappa_2=\kappa_3=\kappa_4=0\end{gathered} \tag{21}$$

- Mass divided over interior and exterior: the insulation is located between two massive components of the wall. The areal heat capacity is distributed between the internal and external node.

$$\begin{gathered}\kappa_1=\kappa_5=\frac{\kappa_m}{2}\\ \kappa_2=\kappa_3=\kappa_4=0\end{gathered} \tag{22}$$

[6] For a summary of the calculation of the properties of the different types of building elements refer to Appendix D.

- Equally distributed mass: there is no insulation. The areal heat capacity is evenly distributed.

$$\kappa_1 = \kappa_5 = \frac{\kappa_m}{8}$$
$$\kappa_2 = \kappa_3 = \kappa_4 = \frac{\kappa_m}{4} \tag{23}$$

- Mass concentrated inside: there is insulation both in the internal and external part of the wall. The middle node gets the whole value of the areal heat capacity of the element.

$$\kappa_3 = \kappa_m$$
$$\kappa_1 = \kappa_2 = \kappa_4 = \kappa_5 = 0 \tag{24}$$

Default values for κ_m are provided in the standard and are shown in Table 12.

Table 12. Values of areal heat capacity of opaque building elements according to the class of construction.

Class	***K_m*** **J/(m²·K)**	**Description of the class**
Very light	50 000	No mass components other than plastic board and/or wood siding, or similar.
Light	75 000	No mass components other than 5-10 cm of lightweight brick or concrete, or similar.
Medium	110 000	No mass components other than, either 10-20 cm of lightweight brick or concrete, or less than 7 cm of solid brick or heavyweight concrete, or similar.
Heavy	175 000	7-12 cm of solid brick or heavyweight concrete, or similar.
Very heavy	250 000	>12 cm of solid brick or heavyweight concrete, or similar.

When it comes to elements in contact with the ground, regardless of the mass distribution, the first two nodes always get the same value:

$$\kappa_1 = 0 \qquad\qquad \kappa_2 = \kappa_{gr} \tag{25}$$

where κ_{gr} is the areal heat capacity of the fixed ground element for a 0.5 m thick ground layer, which is given in EN ISO 13370:2017 [54], and depends on the type of soil, as it is shown in Table 13.

Table 13. Areal heat capacity of the fixed ground element for a 0.5 m thick ground layer.

Type of soil	***K_{gr}*** **J/(m²·K)**
Clay or silt	$1.5 \cdot 10^6$
Sand or gravel	$1.0 \cdot 10^6$
Homogeneous rock	$1.0 \cdot 10^6$

The reason behind these constant values for the elements is simply the influence of the ground on the heat transfer through this medium.

The values for the remaining three nodes according to their mass distribution are:

- Mass concentrated at internal side:

$$\kappa_5 = \kappa_m$$
$$\kappa_3 = \kappa_4 = \kappa_5 = 0 \tag{26}$$

- Mass concentrated at outer side:

$$\kappa_3 = \kappa_m$$
$$\kappa_4 = \kappa_5 = 0 \tag{27}$$

- Mass divided over interior and exterior:

$$\kappa_3 = \kappa_5 = \frac{\kappa_m}{2}$$
$$\kappa_4 = 0 \tag{28}$$

- Equally distributed mass:

$$\kappa_3 = \kappa_5 = \frac{\kappa_m}{4}$$
$$\kappa_3 = \frac{\kappa_m}{2} \tag{29}$$

- Mass concentrated inside:

$$\kappa_4 = \kappa_m$$
$$\kappa_3 = \kappa_5 = 0 \tag{30}$$

When it comes to surface heat exchange coefficients, conventional internal convective and radiative surface heat transfer coefficients are given in EN ISO 13789:2017 [52], and are shown in Table 14.

Table 14. Conventional internal surface heat transfer coefficients, according to the direction of the heat flow.

Surface heat transfer coefficient (W/m²·K)	**Upwards**	**Horizontal**	**Downwards**
Internal convective surface coefficient, $h_{int\ conv}$	5.0	2.5	0.7
Internal radiative surface coefficient, $h_{int\ rad}$	5.13	5.13	5.13

Similar to the case of the areal heat capacity, the calculation of the conductance between nodes of the different building elements depends on their class. The process varies for opaque elements in contact with the external air, opaque elements in contact with the ground and glazed elements[7].

[7] For a summary of the calculation of the properties of the different types of building elements refer to Appendix D.

The conductance between nodes in opaque elements in contact with the external air is calculated as follows:

$$h_1 = h_4 = \frac{6}{R_k} \qquad h_2 = h_3 = \frac{3}{R_k} \tag{31}$$

where R_k is the thermal resistance of the building element *k* in ($m^2 \cdot K$)/W. It can be observed that the total thermal resistance is divided among the nodes in the following manner: one third of the resistance between the second and the third nodes, another third between the third and the fourth and, lastly, one sixth between the surface nodes and the intermediate nodes (first to second node and fourth to fifth).

According to ISO 6946:2017 [32], this thermal resistance is calculated as follows:

$$R_k = \frac{1}{U_k} - R_{si} - R_{se} \tag{32}$$

The U-value is calculated as the inverse of the total thermal transmittance, as shown in Equation (33). For a plane building element with thermally homogeneous layers, this total thermal transmittance is calculated as the sum of all the resistances of the layers. The calculation of the thermal resistance of a layer is indicated in Equation (35). This will be relevant when adding an extra insulation layer as a retrofit measure.

$$U_k = \frac{1}{R_{total}} \tag{33}$$

$$R_{total} = R_{si} + R_{se} + \sum_{layers} R_{layer} \tag{34}$$

$$R_{layer} = \frac{d_{layer}}{\lambda_{layer}} \tag{35}$$

Putting Equation (32), (33) and (34) together, a more straightforward equation for calculating the thermal resistance of the building element *k* is obtained, valid for every opaque building element, except the one in contact with the ground. Note that in this equation the effect of the resistances to the interior and the exterior are left out.

$$R_k = \sum_{layers} R_{layer} \tag{36}$$

The design values for the thermal resistance of the surfaces is provided as well by ISO 6946:2017 and presented in Table 15. Note that these values are the inverse of the sum of the radiative and convective surface coefficients both for external and internal surfaces.

Table 15. Design values for the thermal resistance of the surfaces in contact with air.

Thermal resistance of the surface ($m^2 \cdot K$ /W)	**Upwards**	**Horizontal**	**Downwards**
R_{si}	0.10	0.13	0.17
R_{se}	0.04	0.04	0.04

When it comes to glazed elements, the conductance between nodes is:

$$h_1 = \frac{1}{R_k} \tag{37}$$

where R_k is calculated in the same way as in Equation (32) and the U-value considers the whole window (including frame) and is provided by the manufacturer. Note that there are only two nodes in the glazed elements, therefore the total of the thermal resistance is applied in the heat transfer between the two nodes.

Lastly, for elements in contact with the ground:

$$h_4 = \frac{4}{R_k} \qquad h_3 = \frac{2}{R_k}$$
$$h_2 = \frac{1}{\left(\frac{R_k}{4} + \frac{R_{ground}}{2}\right)} \qquad h_1 = \frac{2}{R_{ground}} \tag{38}$$

where R_{ground} is the thermal resistance of 0.5 m of ground, in $(m^2 \cdot K)/W$, and calculated as:

$$R_{ground} = 0.5/\lambda_{ground} \tag{39}$$

The thermal conductivity of the ground depends on the type of soil. This value is given in EN ISO 13370:2017 [54] and it is shown in Table 16.

Table 16. Thermal conductivity of the ground.

Type of soil	λ_{ground} **W/(m·K)**
Clay or silt	1.5
Sand or gravel	2.0
Homogeneous rock	3.5

Note that in the case of the elements in contact with the ground, the thermal resistance of the building element, R_k, is calculated differently than in the other building elements, as shown in Equation (40).

$$R_k = \frac{1}{U_k} - R_{si} \tag{40}$$

The U-value for the elements in contact with the ground is not an input, unlike the other elements. The calculations for this variable are based in ISO 13370:2017 [54]. The case of a *heated basement* will be taken, i.e., part of the habitable area is located below ground level, as shown in Figure 6.

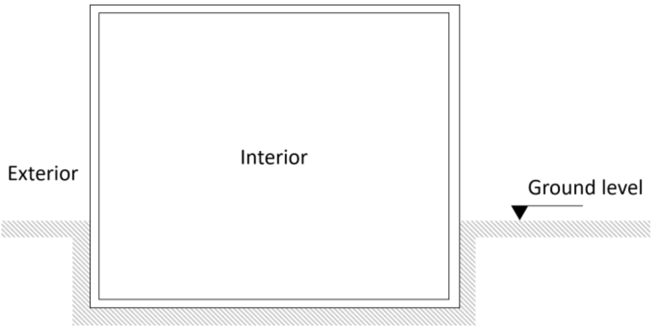


Figure 6. Heated basement.

The reason behind this decision is that the equations for the *slab-on-ground* floor are obtained in case the depth of the basement below ground level, z, is zero.

In this case, there is a distinction between the floor of the basement and the wall of the basement.

The U-value for the basement floor (indicated as *bf* in the subscript) can be calculated according to Equation (41) if the basement floor is poorly or moderately insulated, or according to Equation (42) in case the floor is well insulated.

$$U_{bf} = \frac{2 \cdot \lambda_{ground}}{\pi \cdot B + d_{floor} + 0.5 \cdot z} \cdot \ln\left(\frac{\pi \cdot B}{d_{floor} + 0.5 \cdot z} + 1\right) \qquad \text{if } d_{floor} + 0.5 \cdot z < B \qquad (41)$$

$$U_{bf} = \frac{\lambda_{ground}}{0.457 \cdot B + d_{floor} + 0.5 \cdot z} \qquad \text{if } d_{floor} + 0.5 \cdot z \geq B \qquad (42)$$

Where the geometrical factor *B* is calculated as

$$B = \frac{A_{floor}}{0.5 \cdot Perimeter_{floor}} \qquad (43)$$

The total equivalent thickness, d_{floor}, is calculated with the formula shown in Equation (44), provided in ISO 13370:2017.

$$d_{floor} = d_{walls} + \lambda_{ground} \cdot (R_{si} + R_{floor} + R_{se}) \qquad (44)$$

Regarding the basement walls (*bw* in the subscript), the U-value is calculated according to Equation (45) or Equation (46), depending on the value of the total equivalent thickness for the basement walls, d_{bw}.

$$U_{k,bw} = \frac{2 \cdot \lambda_{ground}}{\pi \cdot z} \cdot \left(1 + \frac{0.5 \cdot d_{floor}}{d_{floor} + z}\right) \cdot \ln\left(\frac{z}{d_{bw}} + 1\right) \qquad \text{if } d_{floor} \leq d_{bw} \qquad (45)$$

$$U_{k,bw} = \frac{2 \cdot \lambda_{ground}}{\pi \cdot z} \cdot \left(1 + \frac{0.5 \cdot d_{bw}}{d_{bw} + z}\right) \cdot \ln\left(\frac{z}{d_{bw}} + 1\right) \qquad \text{if } d_{floor} > d_{bw} \qquad (46)$$

The total equivalent thickness for the basement walls, d_{bw}, is calculated with the formula shown in Equation (47)(44), provided in ISO 13370:2017.

$$d_{bw} = \lambda_{ground} \cdot (R_{si} + R_{bw} + R_{se}) \qquad (47)$$

3.3.1.3 Energy balance: building element level, inside node

When it comes to the inside nodes, i.e. nodes 2 to 4 in the opaque elements (*n=2, 3* or *4*):

$$\frac{\kappa_n}{\Delta t} \cdot (\theta_{n;t} - \theta_{n;t-1}) = h_{n-1} \cdot (\theta_{n;t} - \theta_{n-1;t}) + h_n \cdot (\theta_{n+1;t} - \theta_{n;t}) \tag{48}$$

where all the variables are declared in Equation (18). Note that all the coefficients are referred to the building element *k*.

Rearranging the terms:

$$-h_{n-1} \cdot \theta_{n-1;t} + \left[\frac{\kappa_n}{\Delta t} + h_n + h_{n-1}\right] \cdot \theta_{n;t} - h_n \cdot \theta_{n+1;t} = \frac{\kappa_n}{\Delta t} \cdot \theta_{n;t-1} \tag{49}$$

3.3.1.4 Energy balance: building element level, external surface node

Lastly, in the external surface nodes, i.e. node 1 of every element (*n=1*):

$$\begin{aligned}\frac{\kappa_n}{\Delta t}(\theta_{n;t} - \theta_{n;t-1}) \\ &= h_{ext\,conv} \cdot (\theta_{ext;t} - \theta_{n;t}) + h_{ext\,rad} \cdot (\theta_{ext;t} - \theta_{n;t}) + h_n \\ &\cdot (\theta_{n+1;t} - \theta_{n;t}) + a_{sol} \cdot (I_{dif;t} + I_{dir;t} \cdot F_{sh;t}) - \Phi_{sky;t}\end{aligned} \tag{50}$$

Note that all the coefficients are referred to the building element *k*.

Since in every building element this node will be *n=1*, it can also be expressed in the following way:

$$\begin{aligned}\frac{\kappa_n}{\Delta t}(\theta_{1;t} - \theta_{1;t-1}) = h_{ext\,conv} \cdot (\theta_{ext;t} - \theta_{1;t}) + h_{ext\,rad} \cdot (\theta_{ext;t} - \theta_{1;t}) \\ +h_1 \cdot (\theta_{2;t} - \theta_{1;t}) + a_{sol} \cdot (I_{dif;t} + I_{dir;t}F_{sh;t}) - \Phi_{sky;t}\end{aligned} \tag{51}$$

Rearranging the terms of Equation (51):

$$\begin{aligned}&\left[\frac{\kappa_n}{\Delta t} + h_{ext\,conv} + h_{ext\,rad} + h_1\right] \cdot \theta_{1;t} - (h_1 \cdot \theta_{2;t}) \\ &= \frac{\kappa_n}{\Delta t} \cdot \theta_{1;t-1} + (h_{ext\,conv} + h_{ext\,rad}) \cdot \theta_{ext;t} + a_{sol} \cdot (I_{dif;t} + I_{dir;t}F_{sh;t}) - \Phi_{sky;t}\end{aligned} \tag{52}$$

Conventional external convective and radiative surface heat transfer coefficients are given in EN ISO 13789:2017 [52], and are shown in Table 17.

Table 17. Conventional external surface heat transfer coefficients, according to the direction of the heat flow.

Surface heat transfer coefficient ($W/m^2{\cdot}K$)	Upwards	Horizontal	Downwards
External convective surface coefficient, $h_{ext\,conv}$	20	20	20
External radiative surface coefficient, $h_{ext\,rad}$	4.14	4.14	4.14

For elements in contact with the ground, the value of the external convective and radiative surface heat transfer coefficients is 0. However, to integrate the heat transfer with the ground, these coefficients are substituted by $1/R_{ground\,virtual}$, which is the inverse of the thermal resistance of a virtual ground layer. According to ISO 13370:2017 [54], this thermal resistance is calculated

$$R_{ground\ virtual} = \frac{1}{U_k} - R_{si} - R_{floor} - R_{ground} \tag{53}$$

where R_{ground} is the thermal resistance of 0.5 m of ground, in $(m^2 \cdot K)/W$, and calculated as: $R_{ground} = 0.5/\lambda_{ground}$.

When it comes to the solar absorption coefficient at the external surface depends on the color of the surface. Default values are given in EN ISO 52016-1:2017 [28] and shown in Table 18. The value of this coefficient is 0 for the elements that are in contact with the ground and glazed elements.

Table 18. Default values for solar absorption coefficients according to the color of the external surface.

Type of surface	a_{sol}
Light color	0.3
Intermediate color	0.6
Dark color	0.9

The thermal radiation to the sky is calculated as follows:

$$\Phi_{sky} = F_{sky} \cdot h_{ext\ rad} \cdot \Delta\theta_{sky} \tag{54}$$

The view factor to the sky from the element is 1 for roofs and 0.5 for vertical walls.

The average difference between the apparent sky temperature and the air temperature, $\Delta\theta_{sky}$, is a fixed value. According to the standard:

- 9 K in sub-polar areas,
- 11 K in intermediate zones,
- 13 K in tropics.

For the region of Västra Götalands, the factor $\Delta\theta_{sky}$ will be set to 11 K, as it is an intermediate zone.

3.3.1.5 System of linear equations

As stated before, the strategy for calculating the air temperature and the temperature of the nodes in every time *t*, is by obtaining a linear system of equation with the structure *Ax=B*. Once the coefficients are obtained, it is simple to solve the system by matrix inversion. Considering a large number of coefficients to be solved – matrix A will be 33x33 in the simplest case – it is important to introduce them in the software in a consistent way.

By observing the equations, it can be spotted that a symmetric matrix can be obtained if the area of the element multiplies the balance equations in the building element level[8]. This will simplify the introduction of equations in the solving software.

In order to summarize, in 0 all the final equations in the order in which they will be introduced in the used software can be found.

[8] This is not specified in ISO 52016-1:2017. However, it is simple to observe and it makes both the coding and the equation solving way easier.

3.3.2 Initialization

In order to correctly start running the model, there is a need to give an input of the previous node temperatures. To properly input this data, an initialization simulation is carried out. The simulation consists of the same simulation of the building energy demand, with the difference that only the temperatures are saved. It is made with data for one month, usually from December of the available dataset for the sake of consistency.

3.4 Calculation of the impinging solar radiation on various surfaces

For the sake of simplicity, user-friendliness and versatility, a simple way of calculating the total solar radiation in different planes from the direct and diffuse solar radiation in a horizontal plane has been developed. This model aims to be applied to the weather files provided by Sveby [55], which include the global and diffuse horizontal irradiance.

This simple method relies on geometric relations between planes for transposing the direct radiation and the assumes that diffuse radiation is not dependent on the position of the plane. According to

The geometric relation between the impinging solar radiation in a horizontal plane and the impinging radiation in another plane is expressed in Equation (55).

$$I_{\substack{dir\\wall}} = I_{\substack{dir\\horizontal}} \cdot \frac{cos(\theta)}{sin(\alpha_S)} \tag{55}$$

The direct radiation in the horizontal plane is calculated as the difference between the global radiation and the diffuse radiation in that plane.

According to [56], the angle of incidence is calculated according to the expression in Equation (56).

$$cos(\theta) = sin(\beta) \cdot cos(\alpha_S) \cdot cos(\gamma - \gamma_S) + cos(\beta) \cdot sin(\alpha_S) \tag{56}$$

It is due to mention that this is not the main focus of this project. Therefore the accuracy of this method might not be as good as other models that are currently available. It is recommended to rely on more complicated solar radiation models that can be found in commercial software.

3.5 User interface and data input

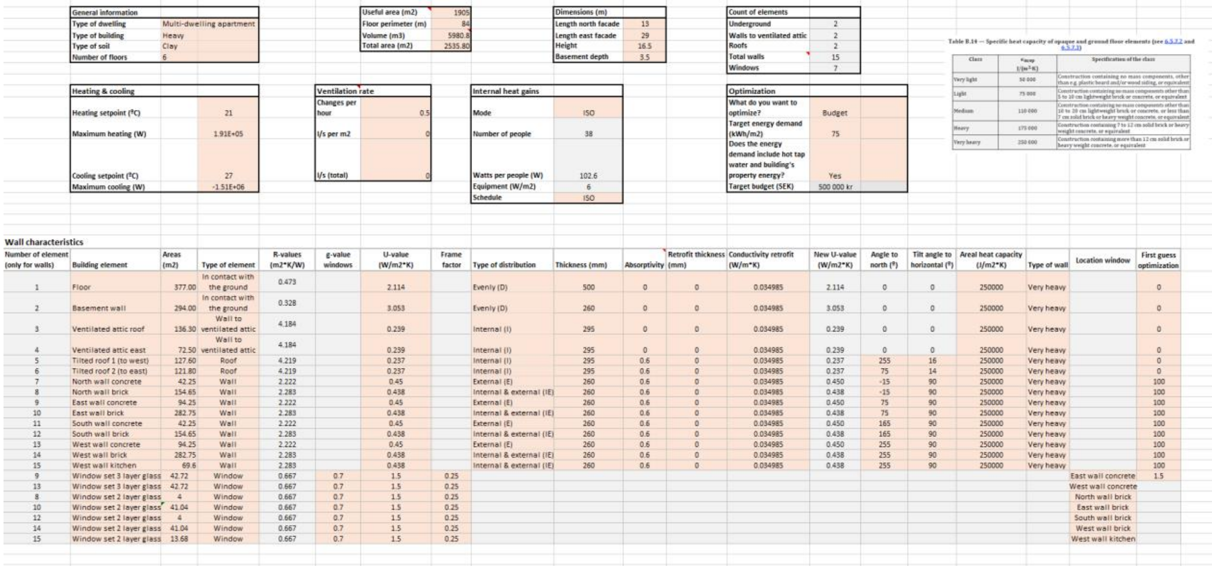
Due to the difficulty of creating user interfaces in Matlab and since programming such a feature would fall out of the scope of this thesis, a complicated user interface for data input has not been created.

However, due to the compatibility that Matlab has to import and export data from EXCEL and how widespread and well-known EXCEL is, a simple user interface in this software has been created. This adds quite some versatility to the Matlab model in terms of user friendliness. Thanks to this EXCEL spreadsheet, all the input data for the building is gathered in the same place.

The usual way that Matlab imports data from EXCEL is by stating the reference of the group of cells where the data is located. This makes the data input very dependent on the location of the data in the spreadsheet and the data input very restricted.

A series of commands in both platforms have been implemented to allow a dynamic search of data. This method allows adding building elements just by copy-pasting a row of data and changing the characteristics of the specified element.

For the sake of user friendliness, a colour code has been placed to specify which cells should receive an input value and which ones should not be altered.



General information	
Type of dwelling	Multi-dwelling apartment
Type of building	Heavy
Type of soil	Clay
Number of floors	6

Useful area (m2)	1905
Floor perimeter (m)	84
Volume (m3)	5980.8
Total area (m2)	2535.80

Dimensions (m)	
Length north facade	13
Length east facade	29
Height	16.5
Basement depth	3.5

Count of elements	
Underground	2
Walls to ventilated attic	2
Roofs	2
Total walls	15
Windows	7

Heating & cooling	
Heating setpoint (ºC)	21
Maximum heating (W)	1.91E+05
Cooling setpoint (ºC)	27
Maximum cooling (W)	-1.51E+06

Ventilation rate	
Changes per hour	0.5
l/s per m2	0
l/s (total)	0

Internal heat gains	
Mode	ISO
Number of people	38
Watts per people (W)	102.6
Equipment (W/m2)	6
Schedule	ISO

Optimization	
What do you want to optimize?	Budget
Target energy demand (kWh/m2)	75
Does the energy demand include hot tap water and building's property energy?	Yes
Target budget (SEK)	500 000 kr

Table B.14 — Specific heat capacity of opaque and ground floor elements (see 6.5.7.2 and 6.5.7.3)

Class	$\kappa_{m,op}$ J/(m²·K)	Specification of the class
Very light	50 000	Construction containing no mass components, other than e.g. plastic board and/or wood siding, or equivalent
Light	75 000	Construction containing no mass components other than 5 to 10 cm lightweight brick or concrete, or equivalent
Medium	110 000	Construction containing no mass components other than 10 to 20 cm lightweight brick or concrete, or less than 7 cm solid brick or heavy weight concrete, or equivalent
Heavy	175 000	Construction containing 7 to 12 cm solid brick or heavy weight concrete, or equivalent
Very heavy	250 000	Construction containing more than 12 cm solid brick or heavy weight concrete, or equivalent

Wall characteristics

Number of element (only for walls)	Building element	Areas (m2)	Type of element	R-values (m2*K/W)	g-value windows	U-value (W/m2*K)	Frame factor	Type of distribution	Thickness (mm)	Absorptivity	Retrofit thickness (mm)	Conductivity retrofit (W/m*K)	New U-value (W/m2*K)	Angle to north (º)	Tilt angle to horizontal (º)	Areal heat capacity (J/m2*K)	Type of wall	Location window	First guess optimization
1	Floor	377.00	In contact with the ground	0.473		2.114		Evenly (D)	500	0	0	0.034985	2.114	0	0	250000	Very heavy		0
2	Basement wall	294.00	In contact with the ground	0.328		3.053		Evenly (D)	260	0	0	0.034985	3.053	0	0	250000	Very heavy		0
3	Ventilated attic roof	136.30	Wall to ventilated attic	4.184		0.239		Internal (I)	295	0	0	0.034985	0.239	0	0	250000	Very heavy		0
4	Ventilated attic east	72.50	Wall to ventilated attic	4.184		0.239		Internal (I)	295	0	0	0.034985	0.239	0	0	250000	Very heavy		0
5	Tilted roof 1 (to west)	127.60	Roof	4.219		0.237		Internal (I)	295	0.6	0	0.034985	0.237	255	16	250000	Very heavy		0
6	Tilted roof 2 (to east)	121.80	Roof	4.219		0.237		Internal (I)	295	0.6	0	0.034985	0.237	75	14	250000	Very heavy		0
7	North wall concrete	42.25	Wall	2.222		0.45		External (E)	260	0.6	0	0.034985	0.450	-15	90	250000	Very heavy		100
8	North wall brick	154.65	Wall	2.283		0.438		Internal & external (IE)	260	0.6	0	0.034985	0.438	-15	90	250000	Very heavy		100
9	East wall concrete	94.25	Wall	2.222		0.45		External (E)	260	0.6	0	0.034985	0.450	75	90	250000	Very heavy		100
10	East wall brick	282.75	Wall	2.283		0.438		Internal & external (IE)	260	0.6	0	0.034985	0.438	75	90	250000	Very heavy		100
11	South wall concrete	42.25	Wall	2.222		0.45		External (E)	260	0.6	0	0.034985	0.450	165	90	250000	Very heavy		100
12	South wall brick	154.65	Wall	2.283		0.438		Internal & external (IE)	260	0.6	0	0.034985	0.438	165	90	250000	Very heavy		100
13	West wall concrete	94.25	Wall	2.222		0.45		External (E)	260	0.6	0	0.034985	0.450	255	90	250000	Very heavy		100
14	West wall brick	282.75	Wall	2.283		0.438		Internal & external (IE)	260	0.6	0	0.034985	0.438	255	90	250000	Very heavy		100
15	West wall kitchen	69.6	Wall	2.283		0.438		Internal & external (IE)	260	0.6	0	0.034985	0.438	255	90	250000	Very heavy		100
9	Window set 3 layer glass	42.72	Window	0.667	0.7	1.5	0.25											East wall concrete	1.5
13	Window set 3 layer glass	42.72	Window	0.667	0.7	1.5	0.25											West wall concrete	
8	Window set 2 layer glass	4	Window	0.667	0.7	1.5	0.25											North wall brick	
10	Window set 2 layer glass	41.04	Window	0.667	0.7	1.5	0.25											East wall brick	
12	Window set 2 layer glass	4	Window	0.667	0.7	1.5	0.25											South wall brick	
14	Window set 2 layer glass	41.04	Window	0.667	0.7	1.5	0.25											West wall brick	
15	Window set 2 layer glass	13.68	Window	0.667	0.7	1.5	0.25											West wall kitchen	

Figure 7. User interface based on an EXCEL spreadsheet for the model.

The data that is required to be introduced in this interface are the dimensions and type of building, the characteristics of all the building elements, the heating and cooling setpoints and maximum capacity, the ventilation rate, the internal heat gains and the optimization variables.

It is due to mention as well that the data from the retrofitting options for the curve fitting in the cost function of the optimization is imported from another EXCEL file using the same principle, i.e. data can be added to the available options just by copying and pasting a row.

This data has not been placed in the same EXCEL spreadsheet as the building input due to lack of time. However, this can easily be introduced in the future.

4. Validation of the model

In order to validate the energy modelling, a case study is modelled. The results of this case study are compared to those of the Carrier's Hourly Analysis Program (HAP) [57]. Thus, a model-to-model validation procedure is carried out. The results of the simulations consist of yearly heating demand in kWh.

4.1 Case description

The weather is based in Gothenburg, Sweden. The weather data is provided by the software Meteonorm [58]. Global solar radiation in all the building elements is provided as an input.

The building consists of a single room with the dimensions presented in Table 19. In the centre of each wall, except the roof, there is a 6 m^2 window. Note that the area of the windows needs to be subtracted from the area of the walls for the input of the model.

Table 19. Dimensions of the building used in the validation case.

Dimension	**Length (m)**	**Building element**	**Area (m^2)**
Height	3	Floor	150
North and south facade length	10	Roof	150
East and west facade length	15	North and south facade	30
Window height	2	East and west facade	45
Window length	3	Windows	6

The characteristics of the different building elements are displayed in Table 20.

Table 20. Characteristics of the walls used in the validation case.

Building element	**Thickness (mm)**	**Overall U-value (W/(m^2·K))**	**Absorptivity**	**Areal heat capacity (J/(m^2·K))**
Floor	Not specified	0.500	Not applicable	Not specified
Roof	136.54	0.685	0.5	207 865
North wall	219.06	1.500	0.7	252 947
East wall	219.06	1.280	0.6	252 947
South wall	304.78	0.901	0.4	293 764
West wall	117.47	1.944	0.5	201 004

The windows present a U-value of 1.5 W/(m^2·K) and an overall shade coefficient of 0.8. As a clarification, HAP uses an overall shade coefficient as an input. In the developed model this input will be treated as a *g*-value. Note that the windows present the same characteristics in every wall.

The setpoints for heating and cooling are 21 and 24 °C respectively. Besides the maximum available heating is 18.8 kW and the maximum available cooling is 509 kW.

The ground thermal conductivity is 2 W/(m·K).

The thermal resistances of the internal and external surface are respectively 0.12064 and 0.05864 (m^2·K)/W. This results in an internal heat transfer coefficient of 8.2891 W/(m^2·K) and an external heat transfer coefficient of 17.0532 W/(m^2·K).

The internal gains of the system are constant throughout the year and account for 6 W/m^2 and 3 people. The ventilation rate is 125 l/s throughout the year.

The test cases are stated in Table 21.

Table 21. Test cases for the validation of the model.

Test case	Retrofitted element	Thickness of insulation (mm)	New U-value (W/m^2·K)	U-value windows (W/m^2·K)
Base case	-	-		-
1	Walls	120		Not changed
2	Walls	240		Not changed
3	Floor	50		Not changed
4	Roof	100		Not changed
5	Windows	No insulation added		0.8
6	Base case with 1 m deep basement	-		-

As well, in order to improve the versatility of the model, a calculation of the direct and diffuse solar radiation in all the building elements based on the direct and diffuse solar radiation in a horizontal surface has been carried out. The goal of this validation is being able to position all the building elements in different orientations.

The calculation has been made according to the procedure explained in section 3.4 and compared with the global radiation previously used. Meteonorm as well provides the solar radiation data in the horizontal plane.

In order to check the validity of the whole model using calculated solar radiation, the test cases are performed again. Besides, an extra case with a different orientation of the walls has been tested. The orientations of the north wall and the west wall have been changed to north-north-east and west-south-west respectively. Even though these directions are not realistic, they serve the purpose of validation.

4.1.1 Assumptions in the model

Since the model differentiates radiation and convection in the internal and external heat transfer coefficients, the values have been adapted from the suggested values in ISO 52016-1:2017. Thus, the taken values are stated in Table 22.

Table 22. Heat transfer coefficients used in the model for the validation.

Coefficient	Surface heat transfer coefficient (W/m^2·K)
Internal convective surface coefficient, $h_{int\ conv}$	2.720
Internal radiative surface coefficient, $h_{int\ rad}$	5.580
External convective surface coefficient, $h_{ext\ conv}$	14.184
External radiative surface coefficient, $h_{ext\ rad}$	2.936

According to the materials of each wall, the mass distribution of the building elements can be seen in Table 23.

Table 23. Distribution of mass of the opaque building elements in the validation case.

Wall	Distribution of mass
Floor	Evenly (D)
Roof	Internal (I)
North	Evenly (D)
East	Evenly (D)
South	Evenly (D)
West	Evenly (D)

The distribution of mass is not altered when the retrofit is applied as the simulations in HAP are carried out by changing the overall U-value of the building element until the U-value with the given retrofit is achieved. A sensitivity analysis regarding this issue will be performed.

Regarding the internal gains, each person adds 102.6 W. Therefore, the total internal gains of the system are: $\Phi_{int} = 6 \cdot A_{use} + 3 \cdot 102.6$ (W).

The areal heat capacity of the ground is taken from the suggestion of the ISO standard, being κ_{gr}= 1.5 $\cdot 10^6$ J/($m^2 \cdot$K).

As stated in the previous section, in the model the overall shade coefficient will be treated as a g-value.

4.2 Results

The results of the test cases for global solar radiation in the different building elements as input and calculated radiation are presented in Table 24 and Table 25, respectively. For a better visualization of the results, they are presented as bar charts.

Table 24. Results of the test cases for the validation of the model.

Test case	Heating demand model (kWh)	Heating demand HAP (kWh)	Relative error heating	Cooling demand model (kWh)	Cooling demand HAP (kWh)	Relative error cooling
Base	39309	39099	0.5%	-3586	-3168	13%
1	22713	25310	10.3%	-4196	-3638	15%
2	21332	24091	11.5%	-4345	-3677	18%
3	38495	38007	1.3%	-3703	-3259	14%
4	31964	32070	0.3%	-3549	-3488	2%
5	37270	37434	0.4%	-3768	-3323	13%
6	40332	41082	1.8%	-3349	-3014	11%

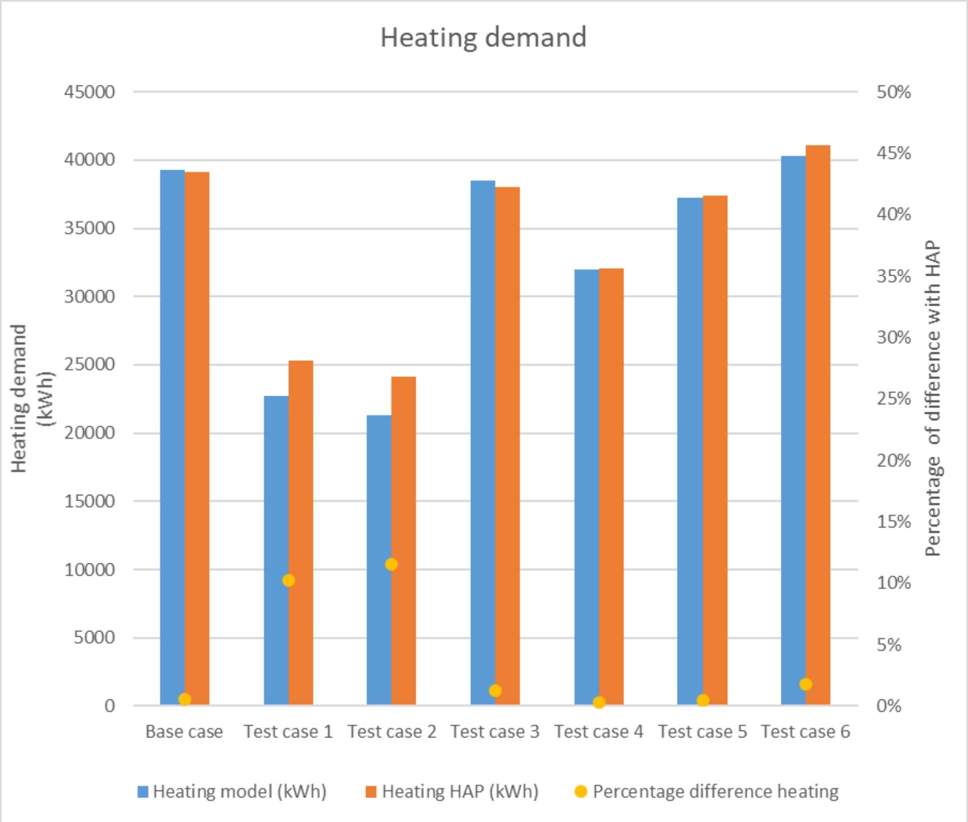


Figure 8. Comparison of heating demands between the developed model and HAP for validation with global radiation as an input.

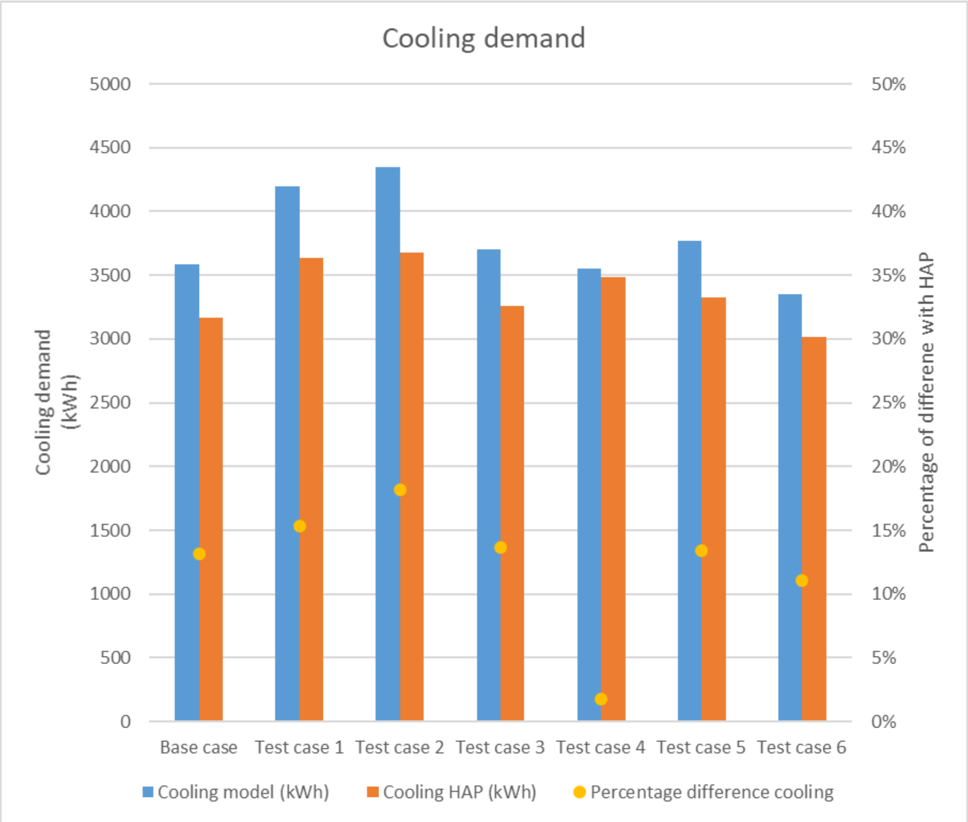


Figure 9. Comparison of cooling demands between the developed model and HAP for validation with global radiation as an input.

From the results of the first set of test cases, where the global radiation in all building elements is taken as an input, it can be seen that the accuracy of the model for heating demand in comparison with HAP is quite high. The most difference can be seen in the test cases 1 and 2, where the difference between the two models reaches 11.6 %, which is still in a range where the results can be accepted as valid.

When it comes to the cooling demand, it can be observed that there is a bigger difference than in heating. However, this must be analysed carefully, since in cold climates –like the one that is being used– the cooling demand is rather low. If the absolute difference between the models is observed, one can realise that the difference between the developed model and HAP is lower than in the case of heating.

It can be observed as well that test case 4, which retrofits the roof, has a behaviour which is notably different from the rest of the cases. This is due to the distribution of the mass in the wall and will be further discussed.

Nevertheless, given that residential buildings in cold climates do not usually have cooling plants, the model will be accepted as valid for simulating the heating demand.

4.2.1 Influence of the mass distribution on the test cases

To test the influence of the mass distribution of the retrofitted walls, the test cases have been repeated with a different structure of the building elements. The results are displayed in Figure 10.

From the results of all the analysed cases, it can be observed that the variations of the heating and cooling demand depending on the thermal mass distribution are not very high. The range of difference between modes is lower than 335 kWh.

In all the cases it can be observed that the heating and cooling demand decreases when the "Internal" distribution is selected. This makes sense mathematically since the heat capacity is all distributed towards the internal surface node, and this node is the one with most influence in the calculation of the operative temperature. The heat capacity softens the effect of extreme temperatures, avoiding peaks in demand.

Following the same reasoning, the demand increases when the "Evenly" distribution is selected and it does increase further if the "External" distribution is on. In these two distributions, the internal surface node gets less and less part of the heat capacity.

Nevertheless, for these cases, the distribution of the mass of the building elements does not play a significant role. According to ISO 52016:1-2017, specifying this results in higher accuracy, thus, it will be used further in this project.

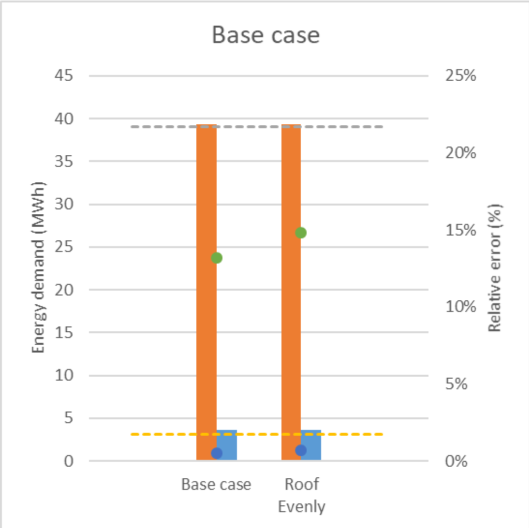


Figure 10a. Base case.

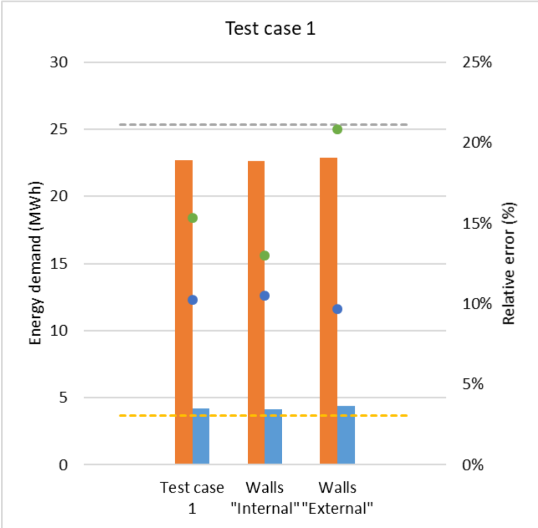


Figure 10b. Test case 1.

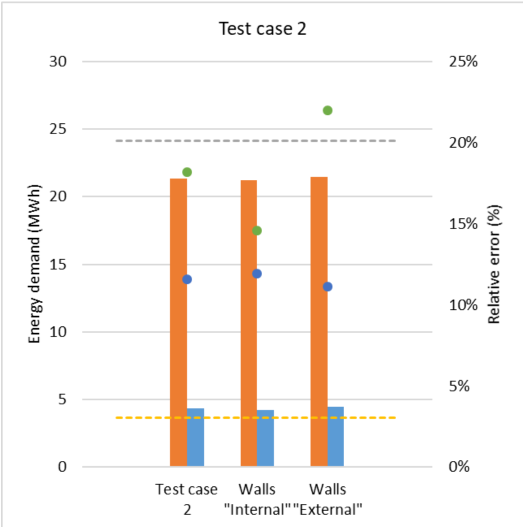


Figure 10c. Test case 2.

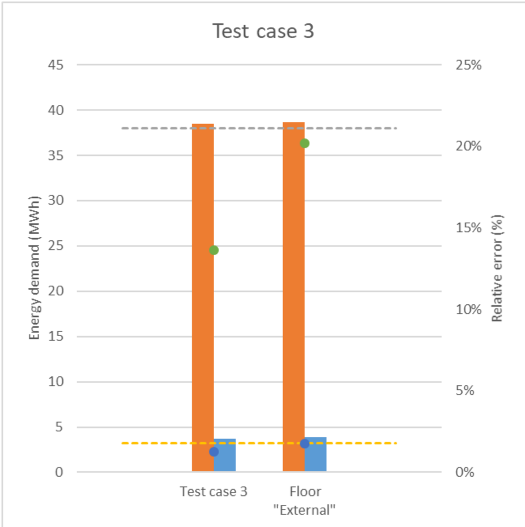


Figure 10d. Test case 3.

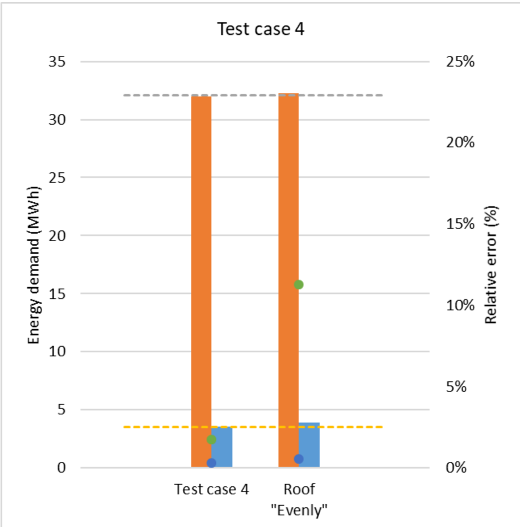


Figure 10e. Test case 4.

Figure 10. Influence of the mass distribution of the walls in different test cases.

4.2.2 Calculation of global radiation in different building elements from direct and diffuse radiation in a horizontal plane

As stated in section 3.4, in order to achieve a higher simplicity, user-friendliness and versatility, a simplified model to calculate solar radiation in different planes has been introduced. In a Figure 11 comparison of the calculated global radiation with the one provided in Meteonorm in different planes is shown.

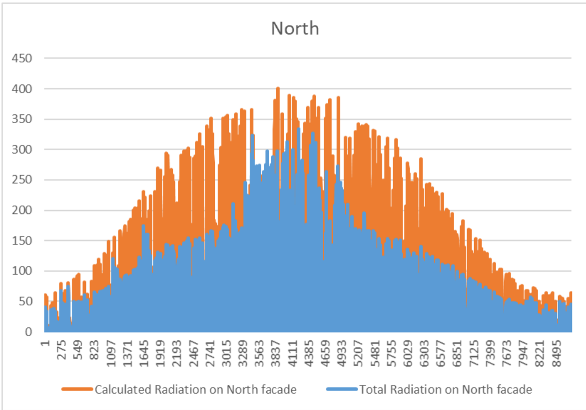


Figure 11a. North façade.

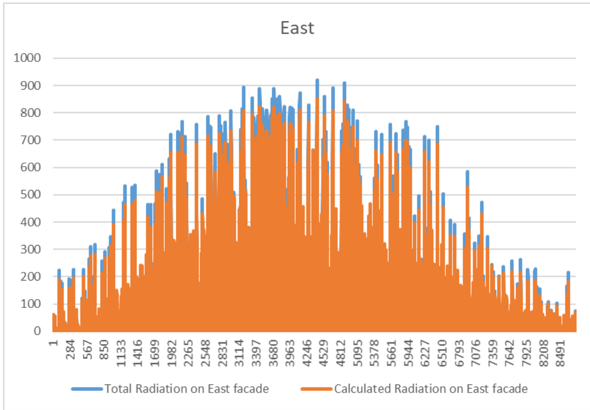


Figure 11b. East façade.

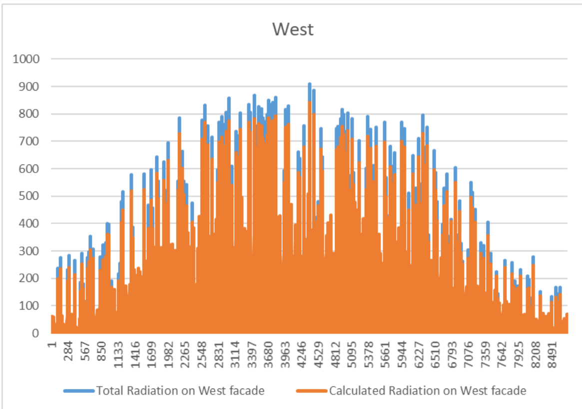


Figure 11c. West façade.

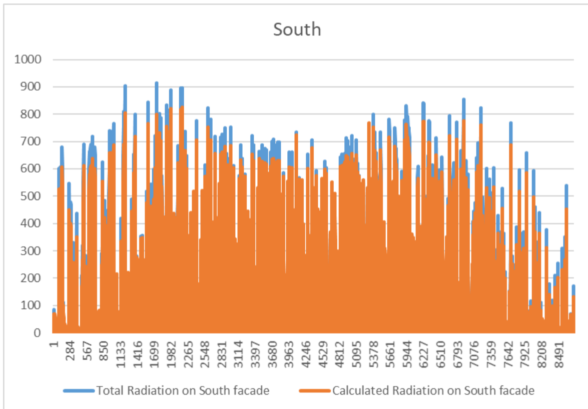


Figure 11d. South façade.

Figure 11. Comparison of the calculated global radiation and the global radiation provided by Meteonorm in different façades.

As it can be observed from the figures, the global solar radiation in the east, south and west façades present a similar behavior to the one provided by Meteonorm. However, the north façade presents a notable difference. In order to solve this, an experimental correction factor of 0.5 has been applied to the diffuse radiation in the case of the north. This coefficient results in a better performance of the solar radiation in this direction. This can be observed in Figure 12.

It is due to mention that the accuracy of this method is not ideal. However, given that the behavior of the calculated solar radiation follows a similar pattern than the one provided by Meteonorm, it will be tested in the energy model.

Coming to the assessment of the performance of the energy modelling with the calculated solar radiation, in Figure 13 and Figure 14, two bar charts with the results from the validation cases are displayed.

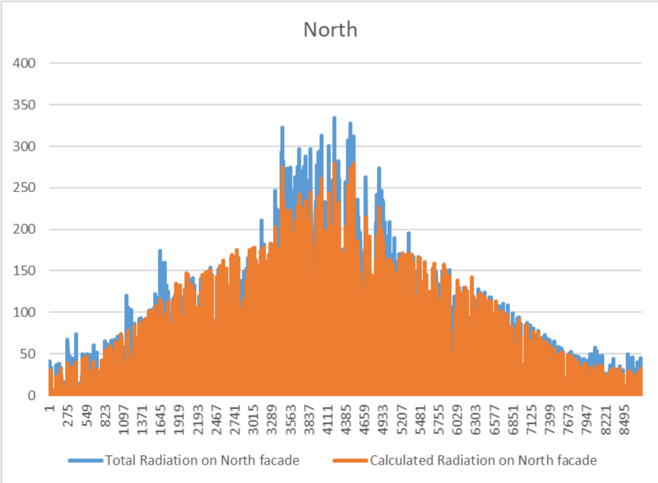


Figure 12. Comparison of the calculated global radiation with a correction factor and the global radiation provided by Meteonorm in the north façades.

For the case of heating demand, as it can be observed, the results are somewhat similar to the ones provided in the first set of cases. Besides, the extra case with the altered positions of some buildings elements has a similar performance than the base case. Thus, the placement of building elements in different orientations can be accepted. Since all these results are still within an acceptable range, the model will be accepted as valid.

When it comes to the cooling demand, it can be observed that the relative error increases considerably as compared to the previous set of test cases. This indicates that the modelling of the solar radiation has a significant impact on the cooling demand.

Table 25. Results of the test cases with calculated solar radiation for the validation of the model.

Test case	**Heating demand HAP (kWh)**	**Heating demand model (kWh)**	**Relative error heating**	**Cooling demand model (kWh)**	**Cooling demand HAP (kWh)**	**Relative error cooling**
Base	38559	39099	1.4%	-3965	-3168	25%
1	22294	25310	11.9%	-4671	-3638	28%
2	20942	24091	13.1%	-4830	-3677	31%
3	37755	38007	0.7%	-4096	-3259	26%
4	31287	32070	2.4%	-4014	-3488	15%
5	36548	37434	2.4%	-4181	-3323	26%
6	39571	41082	3.7%	-3713	-3014	23%
Extra case	38217	38730	1.3%	-4195	-3365	25%

Despite the significant relative error, the model will be accepted due to two main reasons:

Firstly, the absolute error is in the same range than the heating demand. With low cooling demands, low absolute deviations become high relative errors. Lastly and foremost, the studied location has a cold climate. Buildings that are to be renovated in this kind of climates usually do not include any cooling system.

Taking everything into consideration, it can be concluded that both the building modelling and the calculation of the solar radiation can be accepted.

It is due to mention that the aim of this project is not to provide a solar radiation model. For that reason, and due to the similarity on the behavior of the solar radiation and the proximity of the results of the heating demand in the repeated test cases, the solar model will be used in the case study presented in section 0. Nevertheless, the recommendation of the author is to use a more accurate solar radiation model in the future.

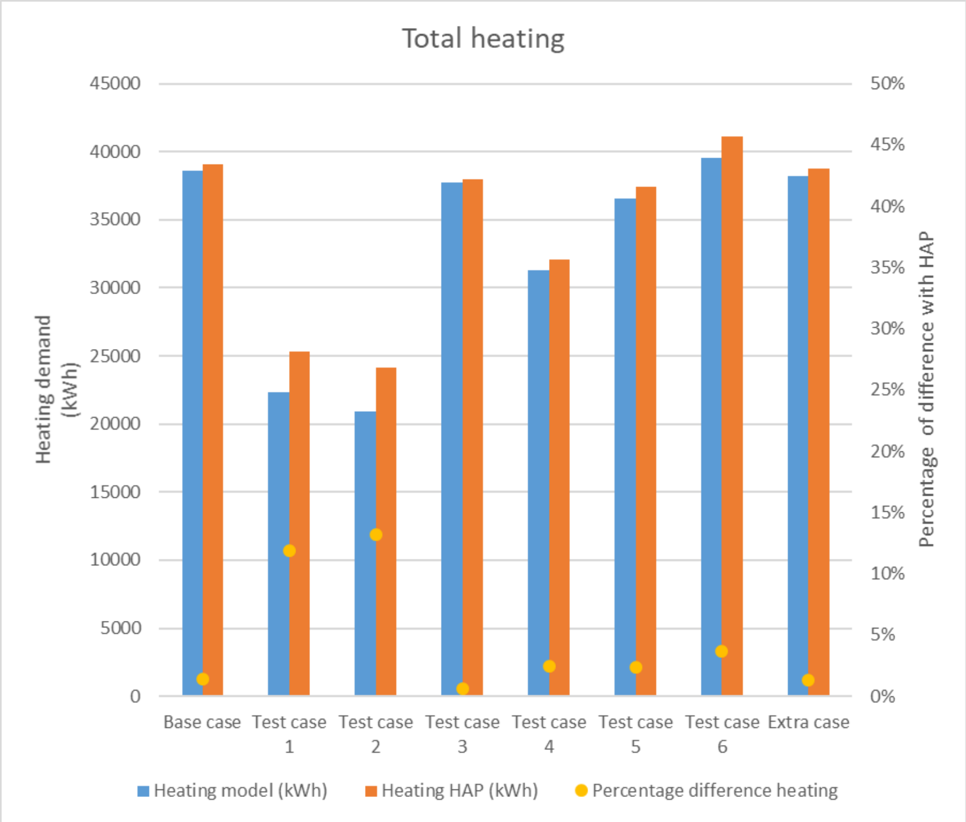


Figure 13. Comparison of heating demands between the developed model and HAP for validation with calculated solar radiation.

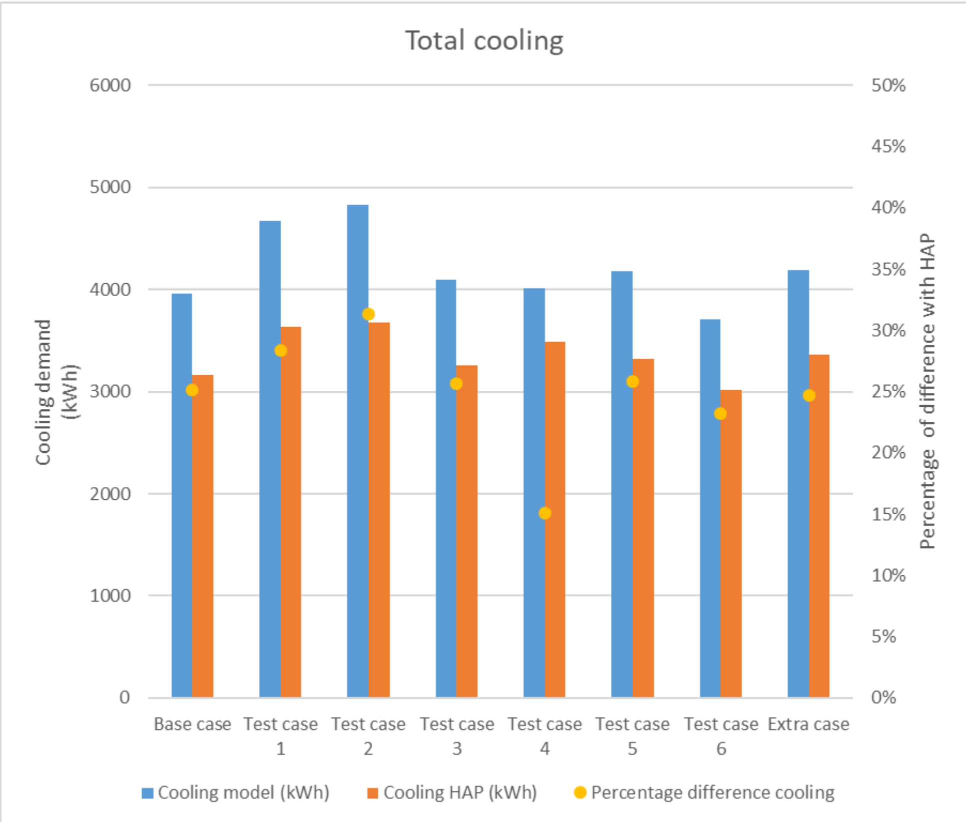


Figure 14. Comparison of cooling demands between the developed model and HAP for validation with calculated solar radiation.

5. Optimization strategy

As stated in the beginning of this report, two different scenarios for optimization will be developed. The first scenario aims to provide the best use of economic resources for an energy demand target. The second one has the goal of minimizing the energy demand for a given budget for renovation.

Note that the way of calculating both energy demand and cost of the retrofitting measures is the same in both scenarios. The only aspect that changes is which is the function to optimize and which is the constraint.

Provided the input for the energy modelling, some other input parameters should be declared, such as the cost per area of the retrofitting options and the corresponding constraint, budget or energy demand, according to the optimization scenario. The input values for the objective function in both scenarios are insulation thickness for walls and U-value for windows

The output of the model is the optimal distribution of the input variables, the optimal budget or energy demand, depending on the optimization scenario. As a post-processing step, the simple payback time is calculated.

The simple payback time is calculated as the total cost of the retrofitting strategy divided by the yearly economic savings according to the price of the energy (district heating, electricity, etc.). Note that the efficiency in the energy transmission from the heating device to the room is assumed to be 1. Thus, the energy savings are slightly underestimated.

5.1 Choice of optimization solver

The original aim of the optimization phase of this project is to provide a time-efficient optimization with a detailed calculation of the space heating energy needs of the building taking into account the interactions between the retrofit options in different building elements. Note that this is one of the pillars upon the decision of the type of optimization.

Regarding the optimization problem, there is a need to consider that, when retrofitting a residential apartment, there is a broad set of options. Commercially, there are a wide variety of insulation types and different windows with different characteristics and prices. From the optimization perspective, these different options consist of a discrete set of characteristics, with no continuous function that relates the different characteristics with a price.

Matlab does not allow a time-efficient optimization strategy that allows having discrete values as inputs. The optimization strategy will be therefore based in continuous cost equations that will be obtained from discrete data.

Given the characteristics of the problem, the used software provides several optimization options. In the following paragraphs, the options that allow constrained optimization will be evaluated.

The first one to be mentioned is linear programming and mixed integer linear programming. These two kinds of optimization strategies solve linear objective functions with linear constraints. Since the problem to solve is not linear, this strategy is not feasible.

There would be a way of using this strategy for solving this problem given a database of measures and their impact on the energy demand and their cost. Nevertheless, this would be very time inefficient if there is a large number of variables with numerous options to be optimized.

Non-linear optimization allows optimizing non-linear objective functions with both linear and non-linear constraints. One of the strengths of this solver is that the gradient of the objective function and the constraints can be specified, making the solver faster if this can be provided. In the case of the energy calculation, this would not be possible, but it would be possible to provide such information for the cost function.

As a drawback for the non-linear optimization solvers, they aim to find local minima, as they are not global optimization tools, i.e., the initial guess plays an essential role in the result of this.

Matlab also offers the possibility to run non-linear optimization algorithms with multiple starting searching points. This can be highly time-consuming.

Another valid option would be using the genetic algorithm. This strategy would make possible the usage of discrete values as well as the continuous value approach. However, this algorithm will not be used due to two main reasons: it is known that genetic algorithms are not time efficient and the usage of this optimization strategy would need a deep and specialized knowledge which falls out of the scope of this Master Thesis.

Having gone through the optimization options that Matlab offers and analyzed them in the context of this project, the selected solver will be *fmincon*, which is the most suitable within the non-linear optimization options. The selected method will be implemented as a local minimum search since the computational time will be lower.

It is essential to be aware of the limitations that this optimization strategy presents and try to overcome them in this context. The main limitations of the selected method are:

- The conversion from the discrete cost values to a continuous cost function allows the solver to provide unrealistic retrofit options. There is a need for postprocessing of information to have a realistic set of options.
- Related to the previous point, the continuous functions in the insulation options have a region between 0 and the first retrofit option with a high steepness; thus, usually, the solver should not provide an answer in that range. However, in some situations, there might be the case where the solver provides a highly unrealistic solution, such as adding 10 millimeters of insulation. It has been tried to overcome this by implementing further constraints not allowing to provide answers in those regions, but it has not been possible.
- As it is a local minimum what the solver looks for, it must be taken into consideration that the solution provided will not be the global optimum, but a local optimum in the range of the initial guess.

5.2 Cost function

Given a series of discrete data, involving cost per area and thickness of insulation or U-value of a window, a polynomic function that goes through all the provided points will be created. This polynomic expression provides the cost per area of building element as a function of either the insulation thickness or the U-value. One function will be calculated for every building element.

The Matlab function *polyfit* allows finding the coefficients of the polynomic function that goes through the points provided.

The total cost function will be the sum of the area of the building element multiplied by the cost of the building element, as depicted in Equation (57).

$$Total\ cost = \sum_{k=1}^{\substack{Number\ of\\ optimization\\ variables}} A_k \cdot f(x) \tag{57}$$

As mentioned before, the selected solver accepts the gradient of this total cost function. Being this total cost the sum of polynomic functions, this can be easily provided.

5.3 Assumptions in the optimization

For the optimization, a series of assumptions and decisions will be made:

- The g-value and the frame factor will be kept constant through the optimization for simplicity.
- The windows will be considered as one building element for the retrofit.
- The mass distribution of the building element will change depending on where the insulation is applied.
- The initial guess will be calculated by allocating a similar thickness of insulation to every wall until a guessed budget is reached. In case this first guess does not provide an acceptable solution, a first guess should be provided manually, according to the current U-values of the building.

When it comes to the decision of the windows being considered as only one variable, the reason behind this choice is stated in the following paragraphs.

Not only will this decision decrease the number of variables and thus the computational time, also it will solve a modelling problem.

Given that the area of the window set and the g-value will remain untouched in the optimization, the solar heat gains through the windows will remain the same. The only variable that changes is the U-value.

The way the heat losses through the window are modelled imply, in this case, the same behaviour and contribution of a window set regardless of its location. Therefore, in case there is symmetry in the building, the behaviour of the symmetric window sets will be the same when changed. In this case, it would make sense to lump together symmetric window sets. Then, for simplicity, all the windows are lumped together as one variable for the optimization.

This would make sense from a practical point of view, as windows are a substantial investment and usually building owners do not want different windows in their façades due to aesthetics. Usually, windows only changed once the lifetime has finished, and in one building windows are installed simultaneously.

6. Case study

The developed model will be applied in a case study. An analysis of the current energy consumption of the building will be made, as well as different cases for retrofit optimization. The considered cases are listed in Table 26.

Table 26. Optimization scenarios applied in the case study.

Case	Description
Case 1	Required retrofitting measures for the compliance with the energy demand requirements of BBR [29].
Case 2	Required retrofitting measures for achieving a 30 % energy saving
Case 3	Required retrofitting measures for achieving a 40 % energy saving
Case 4	Required retrofitting measures for achieving a 45 % energy saving
Case 5	Best retrofit strategy with a maximum budget of 2 000 000 SEK
Case 6	Best retrofit strategy with a maximum budget of 1 500 000 SEK
Case 7	Best retrofit strategy with a maximum budget of 1 000 000 SEK
Case 8	Best retrofit strategy with a maximum budget of 500 000 SEK
Case 9	Best retrofit strategy with a maximum budget of 200 000 SEK

6.1.1 Description of the building and the input to the model

The presented case study consists of an adaptation of a residential building for student housing located in the district of Olofshöjd, in Gothenburg Sweden. This student neighbourhood consists of brick buildings with three to six floors and was built in the period from 1961 to 1971 [59].

Two sketches of the plans of the adapted building can be seen in Figure 15 and Figure 16. It is relevant to highlight that these sketches are just provided for the reader to have an understanding of the shape of the building. The important input data for the model is provided in Table 27.

The assumptions made in the modelling of the building are the following:

- All the floor area of the building is intended to be heated to a comfort temperature.
- The ventilated attic is treated as the exterior. However, it blocks the solar radiation and, consequently, the absorptivity of the walls facing this part of the building is set to 0.

6.1.2 Input data

The building is divided into 14 different opaque building elements and 7 sets of windows. In Figure 17, a schematic distribution of the walls can be observed.

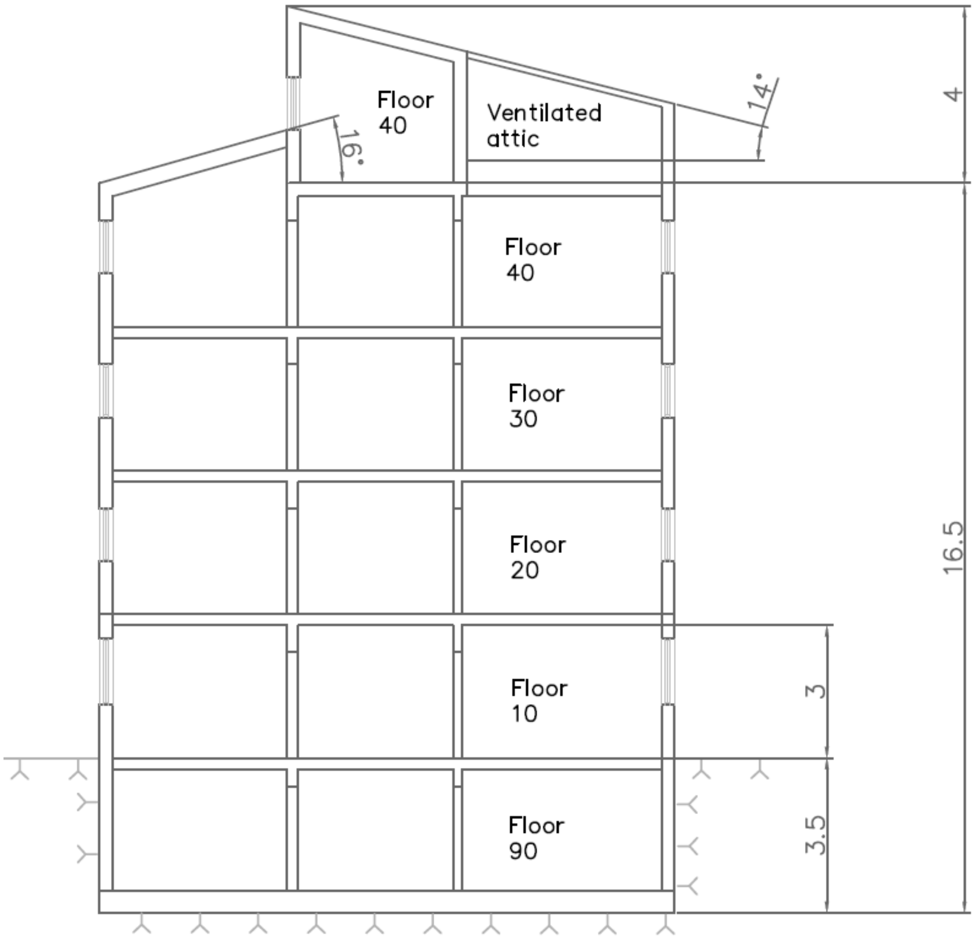


Figure 15. Sketch of the section of the building used for the case study.

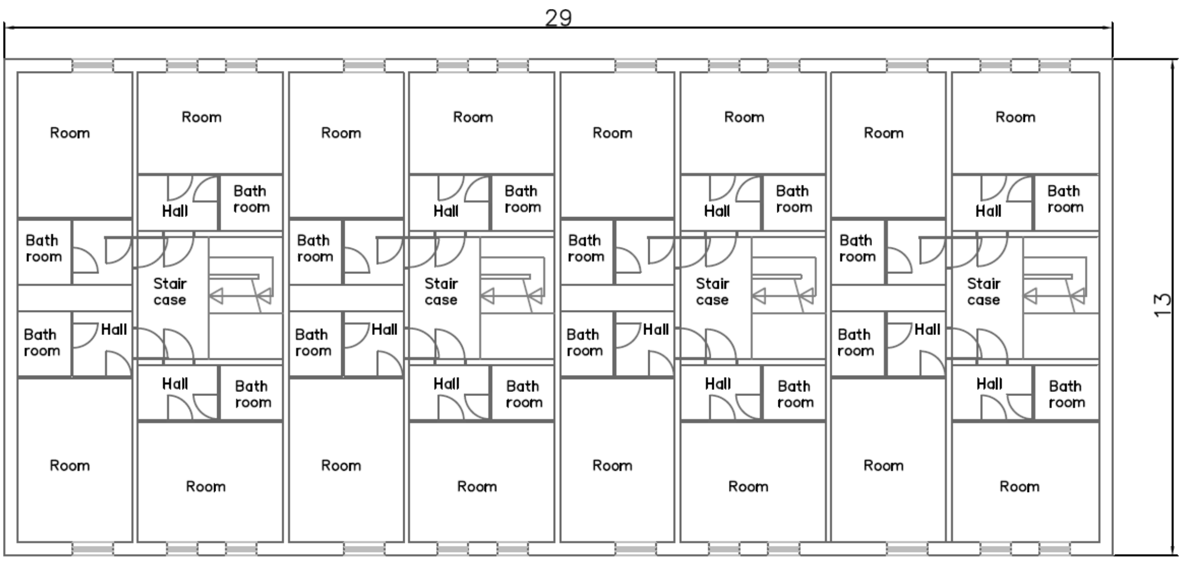


Figure 16. Sketch of the plan of one of the floors of the building used for the case study.

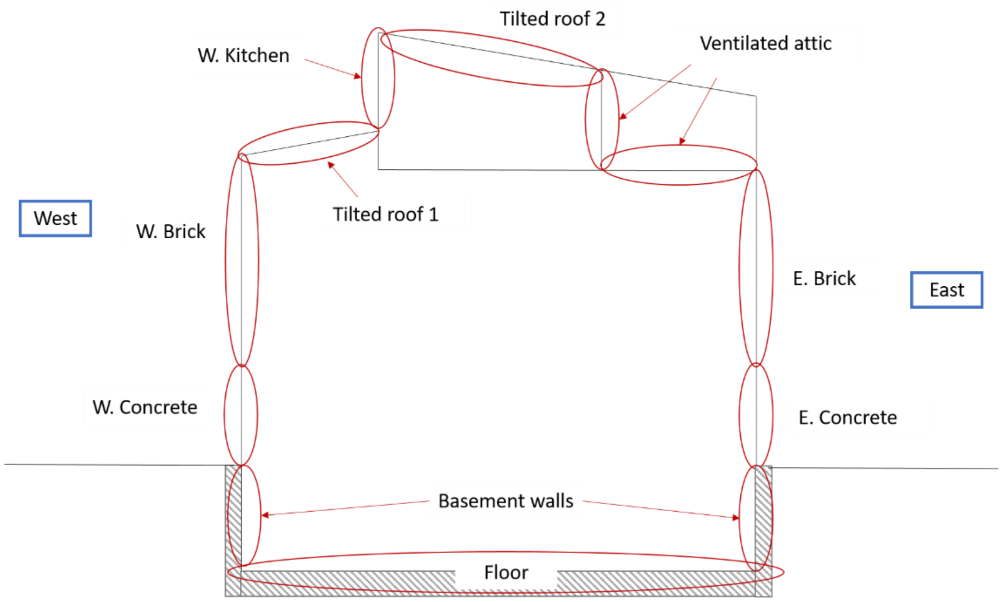


Figure 17. Schematic of the case for visualization of the location of the different building elements.

Table 27. Characteristics of the opaque building elements in the case study.

Building element	**U-value (W/m^2K)**	**Mass distribution**	**Type of wall**	**Absorptivity**
Floor	2.114	Evenly (D)	Very heavy	0
Basement wall	3.053	Evenly (D)	Very heavy	0
Ventilated attic	0.239	Internal (I)	Very heavy	0
Tilted roof 1 (to west)	0.237	Internal (I)	Very heavy	0.6
Tilted roof 2 (to east)	0.237	Internal (I)	Very heavy	0.6
North wall concrete	0.45	External (E)	Very heavy	0.6
North wall brick	0.438	Internal & external (IE)	Very heavy	0.6
East wall concrete	0.45	External (E)	Very heavy	0.6
East wall brick	0.438	Internal & external (IE)	Very heavy	0.6
South wall concrete	0.45	External (E)	Very heavy	0.6
South wall brick	0.438	Internal & external (IE)	Very heavy	0.6
West wall concrete	0.45	External (E)	Very heavy	0.6
West wall brick	0.438	Internal & external (IE)	Very heavy	0.6
West wall kitchen	0.472	Internal & external (IE)	Heavy	0.6

Table 28. Dimensions and location of the opaque building elements in the case study.

Building element	**Area[9] (m2)**	**Thickness (mm)**	**Angle to north (°)**	**Tilt angle (to horizontal) (°)**
Floor	377.00	500	0	0
Basement wall	294.00	260	0	0
Ventilated attic	208.80	295	0	0
Tilted roof 1 (to west)	127.60	295	255	16
Tilted roof 2 (to east)	121.80	295	75	14
North wall concrete	42.25	260	-15	90
North wall brick	154.65	260	-15	90
East wall concrete	94.25	260	75	90
East wall brick	282.75	260	75	90
South wall concrete	42.25	260	165	90
South wall brick	154.65	260	165	90
West wall concrete	94.25	260	255	90
West wall brick	282.75	260	255	90
West wall kitchen	69.60	260	255	90

The windows have a U-value of 1.5 W/m^{2}K, a g-value of 0.7 and a framing factor of 0.25. The position of the window sets and their areas are shown in Table 29

Table 29. Position and areas of window sets of the case study.

Location of the window	**Area (m^2)**
East wall concrete	42.72
West wall concrete	42.72
North wall brick	4.00
East wall brick	41.04
South wall brick	4.00

[9] This area includes the area of the windows. The model extracts this area from the opaque building elements for the mathematical expressions.

West wall brick	41.04
West wall kitchen	13.68

Table 30. Input values for different variables for the case study.

Ventilation rate (changes per hour)	0.5
Heating setpoint (ºC)	21
Maximum heating power (W)	10^6
Internal gains	According to ISO
Schedule	According to ISO
Type of dwelling	Multi-dwelling apartment
Type of soil	Clay
Floor perimeter (m)	84
Useful area (m^2)	1905
Volume (m^3)	5981
Floors	6 (not the same area)

6.2 Cost functions

The commercial data used for the cost function has been provided by the division of Building Technology of Chalmers University of Technology [60], and comprises current prices for the overall process of retrofitting, including material acquisition and installation.

The discrete values for the considered retrofit options can be observed in the tables below. The obtained polynomic functions are represented graphically in Figure 18.

Table 31. Properties of the different retrofitting measures applied to the case study.

Building element	Walls	Roofs	Floor and basement
Side	Internal	Internal	Internal
Thermal conductivity (W/mK)	0.034965	0.034965	0.034965

Table 32. Cost of the different retrofitting measures applied to the case study.

Walls		**Roofs**		**Floor and basement**		**Windows**	
Thickness (mm)	**Cost (SEK)**	**Thickness (mm)**	**Cost (SEK)**	**Thickness (mm)**	**Cost (SEK)**	**U-value ($W/m^2·s$)**	**Cost (SEK)**
0	0	0	0	0	0	1.5	0
50	1558.37	100	446.00	50	689.84	1.2	6778.75
80	1572.37	150	484.00	70	702.94	1.1	7705.30
100	1599.37	250	570.50	100	733.61	0.8	9073.52
150	1696.26	300	611.50	--	--	--	--

170	1758.14	--	--	--	--	--	--
200	1789.37	--	--	--	--	--	--

It is important to point out that the cost per square meter of the least expensive window retrofit is almost four time as costly as the most expensive insulation option. This will have a big impact in the optimization, as the windows will be a less preferable option for retrofitting.

For this reason, the initial guess will always be not to retrofit the windows.

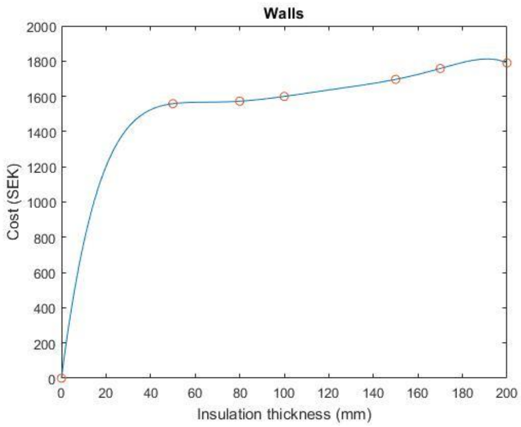


Figure 18a. Retrofit in walls.

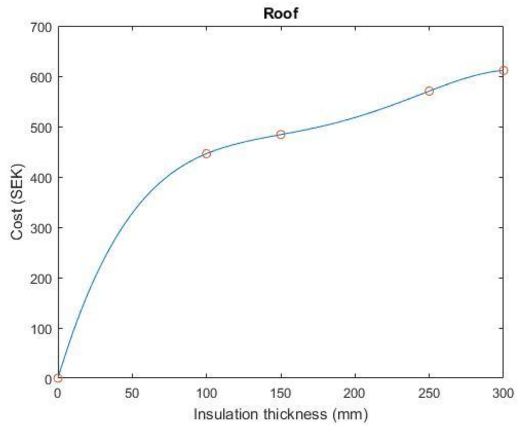


Figure 18b. Retrofit in the roof.

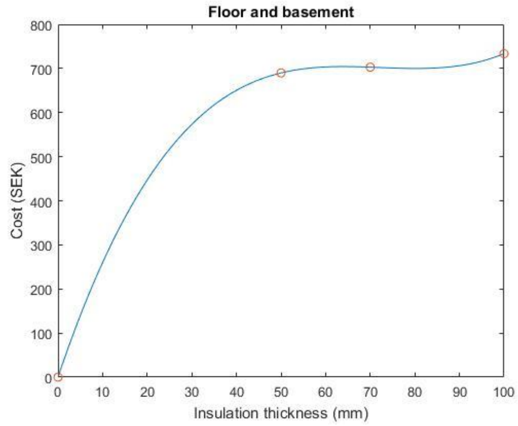


Figure 18c. Retrofit in floor and basement.

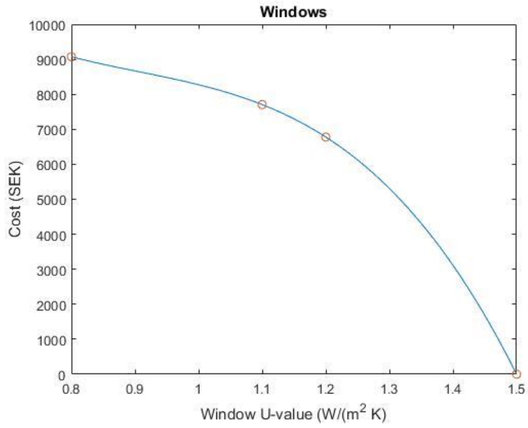


Figure 18d. Retrofit in windows.

Figure 18. Representation of the polynomic functions obtained from the discrete data of the retrofit options in different building elements.

6.3 Economic aspects

According to Göteborg Energi [61], which is the main provider of district heating in the Gothenburg region, the price for this service for private persons[10] is calculated monthly according to Equation (58). The price is calculated in Swedish Crowns (SEK) and the heating demand in kWh.

[10] For businesses, including property owners, the calculation is more complicated than the one shown before. It considers peak consumptions and the temperature of the return water. The calculation of these variables falls out of the scope of this thesis, thus the price for private persons will be used.

$$\text{Price} = 350 + 0.844 \cdot Q_H \tag{58}$$

Thus, when calculating the economic savings yearly, the calculation will be done by multiplying the energy savings in comparison to the base case, multiplied by the coefficient in the previous equations.

Simple payback time will be calculated for having a rough economic indicator. It will be calculated as the total cost of the optimal retrofit solution divided by the yearly savings. However, if a more detailed economic analysis is to be carried out, other indicators such as the Net Present Value should be included.

6.4 Results

6.4.1 Current energy performance of the building

Running the energy simulation with the previous conditions a total of 108140 kWh is accounted for space heating, which, in specific units, is 56.76 kWh/m^2.

In the context of the Swedish Building Regulation, BBR [29], apart from the space heating demand, the energy use for comfort cooling, production of hot tap water and building's property energy must be considered. This is called the building's specific energy use.

Given that in the building there are no comfort cooling facilities, this energy will be neglected. According to Sveby [30], for multi-dwelling apartments, a recommended input value for the energy used to produce hot tap water is 25 kWh/m^2.

Lastly, an estimation of the building's property energy has been taken into account, considering 4 luminaires of 50 W per floor in the 4 upper floors plus a total of 8 in the basement. All those luminaires are assumed to be always on. That results in 10512 kWh yearly, and considering the total useful area, 5.52 kWh/m^2.

Therefore, the total specific energy use is 87.28 kWh/m^2, which is a very fair value for a building built in this year. Nevertheless, this is 12.28 kWh/m^2 more than the value for complying with the applicable regulation for new buildings, which is the first scenario subject to study.

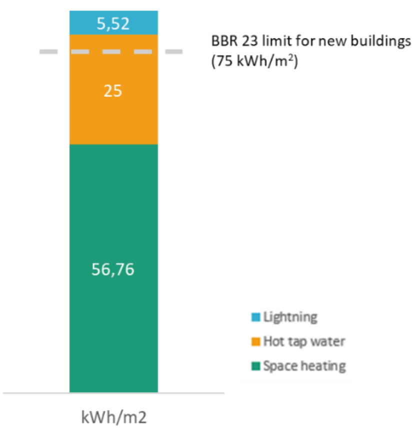


Figure 19. Distribution of energy demand in the building's specific energy use.

A first retrofitting run has been tried applying all the available retrofitting measures, in order to know the capacity of this set of options. The achieved result is a specific heat demand of 26.86 kWh/m^2, which is a reduction of slightly more than 50 %.

Unfortunately, with this set of measures, it would not be possible to achieve the limit imposed by the EnerPHit certification developed by the Passive House Institute [25], which lays in 25 kWh/m^2. In order to achieve this limit, other retrofitting strategies that might be more costly should be taken into consideration, such as ventilation flow strategies, heat recovery systems or heat pumps.

6.4.2 Optimization results

The results are shown in Table 33 and Table 34.

As it was expected, due to the approximation from the discrete data to the continuous function, the results do not show exact values except in the saturation points. For this reason, to provide a realistic solution, the results should be rounded to the closest value and the cost, energy demand and payback time recalculated, in a postprocessing stage. The recalculated data is presented in

Table 36 and

Table 37.

It is relevant to mention that case 5 converged into a not reasonable solution. Given that the budget constraint is 2 million SEK, the solution found is not satisfactory, as it reaches a similar heating demand as case 1, which uses roughly half of the budget. For this reason, this specific case has been rerun with a different initial guess. The initial guess has been chosen manually according to the U-values of the walls.

In this case, it can be seen that the payback period is more similar to case 6. The achieved energy demand is between case 2 and 3, which makes sense, as the budget of case 5 also falls between those 2 cases.

Table 33. Optimization results for the cases with a specific energy target.

	Case 1	**Case 2**	**Case 3**	**Case 4**
Energy target (kWh/m2)	44.48	39.73	34.06	31.22
Cost (SEK)	1 063 558 kr	1 677 500 kr	2 473 223 kr	3 979 578 kr
Payback time (years)	54.1	61.6	68.1	97.3
Computational time (hours)	2.71	2.18	3.06	2.23
Optimal retrofit	-	-	-	-
Floor	0	0	0	100
Basement wall	91	94	100	100
Ventilated attic	0	0	0	200
Tilted roof 1 (to west)	175	195	300	300
Tilted roof 2 (to east)	169	300	300	300
North wall concrete	0	0	200	200
North wall brick	200	139	200	200
East wall concrete	200	0	200	200
East wall brick	0	138	200	200
South wall concrete	0	0	200	200
South wall brick	200	200	200	200
West wall concrete	0	0	200	200
West wall brick	0	137	200	200

West wall kitchen	200	0	200	200
Windows	1.5	1.5	1.46	1.26

Table 34. Optimization results for the cases with a specific budget target.

	Case 5	**Case 6**	**Case 7**	**Case 8**	**Case 9**
Budget target (SEK)	2 000 000 kr	1 500 000 kr	1 000 000 kr	500 000 kr	200 000 kr
Energy demand (kWh/m^2)	44.49	41.82	45.07	49.70	53.54
Payback	101.9	62.7	53.5	44.3	38.9
Hours	3.50	2.72	2.49	1.60	0.82
Optimal retrofit	-	-	-	-	-
Floor	0	0	0	0	0
Basement wall	96	100	95	100	47
Ventilated attic	0	0	0	0	0
Tilted roof 1 (to west)	212	300	300	300	0
Tilted roof 2 (to east)	206	300	200	300	0
North wall concrete	0	200	200	0	0
North wall brick	0	0	0	0	0
East wall concrete	0	200	0	17	0
East wall brick	0	17	145	0	0
South wall concrete	0	200	145	200	0
South wall brick	0	0	0	0	0
West wall concrete	0	200	0	0	0
West wall brick	0	200	0	0	0
West wall kitchen	0	200	146	0	0
Windows	0.88	1.5	1.5	1.5	1.5

From an economic point of view, observing the simple payback time of all the results, it can be concluded that the great majority of these retrofit strategies would not be worth doing, since the payback period exceeds the lifetime of the measures, which usually are fixed in 50 years. The only cases where investing would be reasonable is in cases 8 and 9.

These two cases are the ones that require the least investment, which makes sense since the building has already a high performance. It is interesting to mention that in both cases the basement is retrofitted. This part of the building is the one that presents the highest U-value and the second biggest area.

In case 8 it can be observed that both roofs are also retrofitted, apart from the basement and the south concrete wall. The roofs present quite a low U-value. However, the price of the retrofit in these parts is almost three times lower than any retrofitting in another wall, making this a very cost-effective measure.

It is due to note that in case 4, which is the one with the most restrictive energy target, the insulation in all elements has reached its limits, whereas the retrofitting of the windows has not. This indicates, as it was stated in Section 6.2, that window replacement is not a cost-effective measure because of the elevated price of this option.

Table 35. Repetition of case 5 with a different initial guess.

	Case 5	
Budget target (SEK)	2 000 000 kr	
Energy (kWh)	37.05	
Payback	63.4	
Hours	0.97	
	Optimal retrofit	**Initial guess**
Floor	0	0
Basement wall	100	100
Ventilated attic	0	0
Tilted roof 1 (to west)	0	0
Tilted roof 2 (to east)	0	0
North wall concrete	166	150
North wall brick	165	150
East wall concrete	165	150
East wall brick	163	150
South wall concrete	163	150
South wall brick	162	150
West wall concrete	164	150
West wall brick	163	150
West wall kitchen	165	150
Windows	1.5	1.5

The post-processing has been done manually, approaching the insulation thickness to a close option among the available ones. It has been attempted to comply with the constraints, so it has not always been possible to round to the closest option.

Paying attention to case 3, three different options came to light: retrofitting the windows, the ventilated attic or the floor. The three cases have been run. From the results, it can be observed that the case where the ventilated attic is retrofitted is more favourable since it still complies with the energy restriction.

The only case where the constraints could not be met is in case 9, where the minimum budget for retrofitting the whole basement is roughly 3000 SEK higher than the budget constraint. It is due to highlight that this amount is remarkably low.

After the postprocessing, it can be observed that the objective function and the constraints remain close to the original ones. There is no more than a 5 % increase in the budget in cases where there is an energy target and less than 1 % difference in the energy consumption in the cases where the budget is limited.

In Figure 20 and Figure 21 a graphic visualization of the results after postprocessing is displayed.

From the plots, it can be observed that the energy consumption decreases when the investment in the retrofit increases, although there is a deceleration in the energy savings as the budget grows. As well, the payback time increases with the investment, which is congruent with the previous statement.

Table 36. Optimization results for the cases with a specific energy target after postprocessing.

	Case 1	**Case 2**	**Case 3 (option 1)**	**Case 3 (option 2)**	**Case 3 (option 3)**	**Case 4**
Original energy target (kWh/m2)	44.48	39.73	34.06	34.06	34.06	31.22
Achieved energy demand after postprocessing (kWh/m2)	44.47	39.48	31.58	34.17	33.45	30.61
Original cost (SEK)	1 063 558 kr	1 677 500 kr	2 473 223 kr	2 473 223 kr	2 473 223 kr	3 979 578 kr
Cost after postprocessing (SEK)	1 067 796 kr	1 697 037 kr	3 490 559 kr	2 484 591 kr	2 581 640 kr	4 140 751 kr
Original payback time (years)	54.1	61.6	68.1	68.1	68.1	97.3
Payback time after postprocessing (years)	54.3	61.4	86.7	68.7	69.2	99.0
Optimal retrofit	-	-	-	-	-	-
Floor	0	0	0	100	0	100
Basement wall	100	100	100	100	100	100
Ventilated attic	0	0	0	0	200	200
Tilted roof 1 (to west)	150	150	300	300	300	300
Tilted roof 2 (to east)	150	300	300	300	300	300
North wall concrete	0	0	200	200	200	200
North wall brick	200	150	200	200	200	200
East wall concrete	200	0	200	200	200	200
East wall brick	0	150	200	200	200	200
South wall concrete	0	0	200	200	200	200
South wall brick	200	200	200	200	200	200
West wall concrete	0	0	200	200	200	200
West wall brick	0	150	200	200	200	200
West wall kitchen	200	0	200	200	200	200
Windows	1.5	1.5	1.2	1.5	1.5	1.2

Table 37. Optimization results for the cases with a specific budget target after postprocessing.

	Case 5	**Case 6**	**Case 7**	**Case 8**	**Case 9**
Original budget target (SEK)	2 000 000 kr	1 500 000 kr	1 000 000 kr	500 000 kr	200 000 kr
Budget achieved after postprocessing (SEK)	1 978 362 kr	1 236 374 kr	985 477 kr	443 790 kr	202 813 kr
Original energy demand (kWh/m^2)	37.05	41.82	45.07	49.70	53.54
Energy demand after postprocessing (kWh/m^2)	37.29	42.71	45.47	49.92	53.44
Original payback time (years)	63.4	62.7	53.5	44.3	38.9
Payback time after postprocessing (years)	63.5	55.0	54.6	40.5	38.2
Optimal retrofit	-	-	-	-	-
Floor	0	0	0	0	0
Basement wall	100	100	100	100	50
Ventilated attic	0	0	0	0	0
Tilted roof 1 (to west)	0	300	300	300	0
Tilted roof 2 (to east)	0	300	200	300	0
North wall concrete	170	200	200	0	0
North wall brick	170	0	0	0	0
East wall concrete	170	200	0	0	0
East wall brick	150	0	100	0	0
South wall concrete	150	200	150	200	0
South wall brick	150	0	0	0	0
West wall concrete	150	200	0	0	0
West wall brick	150	200	0	0	0
West wall kitchen	170	200	150	0	0
Windows	1.5	1.5	1.5	1.5	1.5

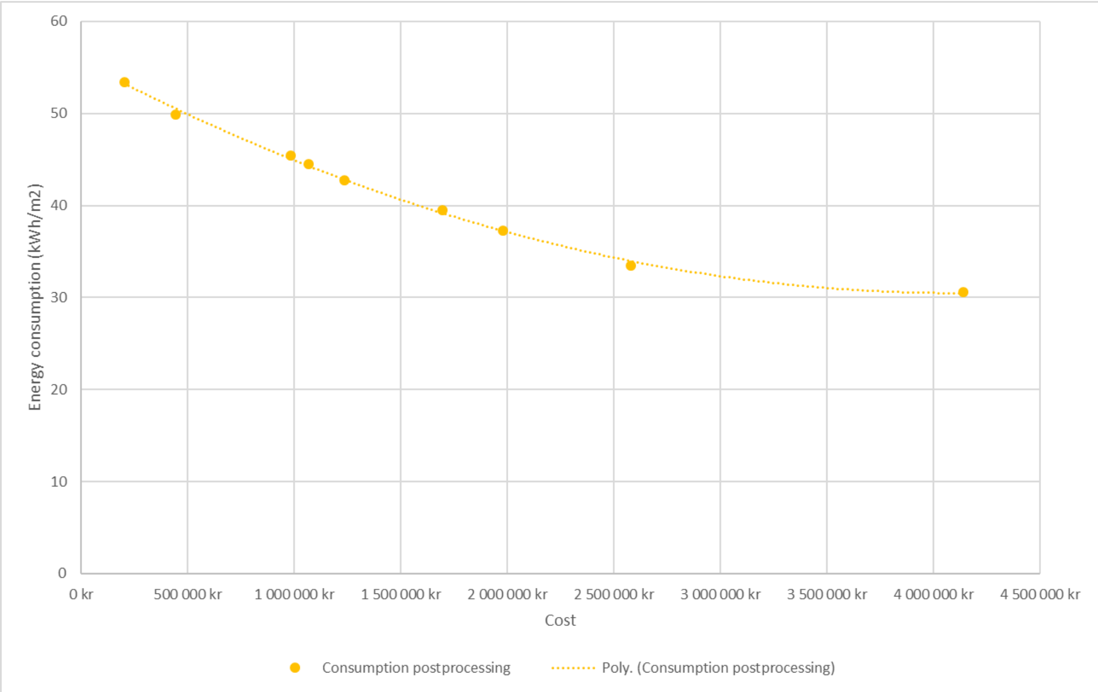


Figure 20. Energy consumption vs. cost of all the optimization cases in the case study after postprocessing.

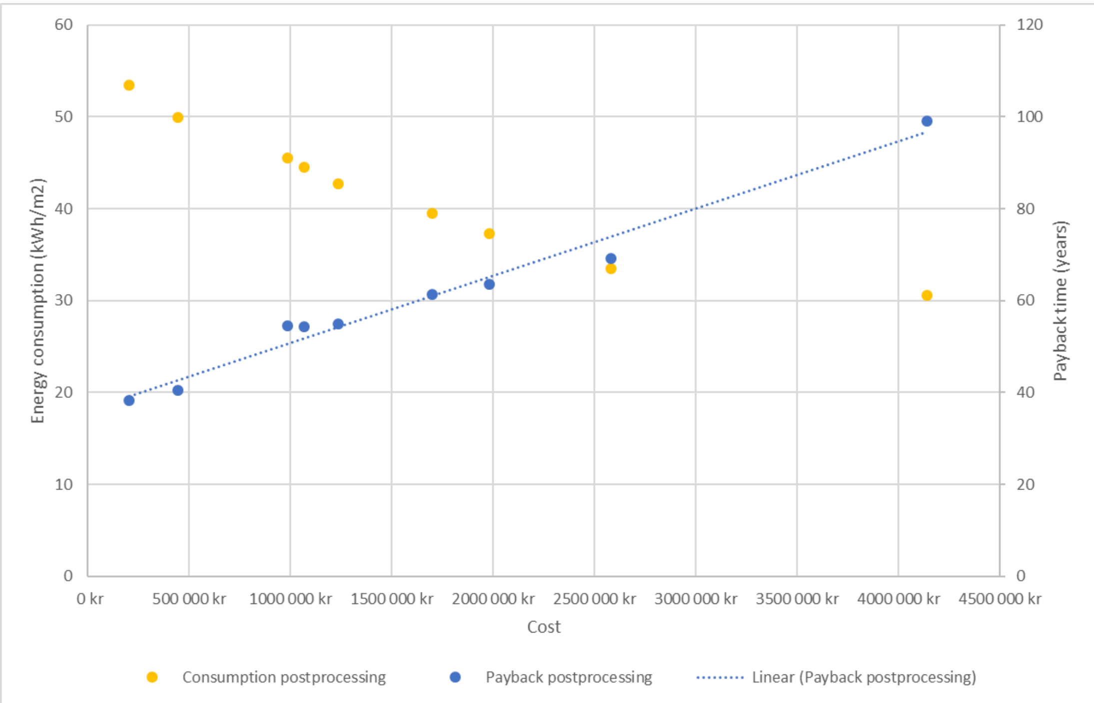


Figure 21. Energy consumption vs. cost and payback time vs. cost of all the optimization cases in the case study after postprocessing.

7. Discussion and conclusions

In this section, the strengths, limitations and future developments of the model will be discussed, along with the conclusions of the project.

7.1 Strengths of the model

This simplified modelling takes into account the properties of the different building elements separately, unlike other modelling strategies that take into account an overall U-value of the building. Besides, the opaque building elements are modelled according to their mass distribution, which has an impact on the accuracy of the model. These two reasons make this way of modelling very adequate when analysing an existing building and the possible addition of insulation.

As well, the fact that the time step is hourly makes the model take into consideration several aspects that other simplified modelling does not take into consideration or does not model in a reliable manner, such as solar heat gains or thermal inertia.

In this direction, the model accuracy when it comes to heating demand is below 15 % in every studied case in the validation, which is a more than acceptable range for a simplified calculation of energy demand. This makes the model reliable and applicable.

The developed tool is as well simple to use, as all the required input is introduced in an Excel spreadsheet, which is a friendly and widespread platform. Once the building characteristics are known, it takes little time to introduce the input data.

The computational time for the calculation of heating demand for one building for one year, once the building data is imported is less than 8 seconds, in the computer used for the simulations in this project. This allows optimizing the retrofitting options for simple buildings, i.e. four walls, the floor, the roof and a set of windows with similar characteristics in each wall, in ranges of 0.5 to 1 hour.

As it is to be expected, the more variables that are added to the retrofit optimization model, the higher the computational time becomes. The computational time for solving the presented case study, which included 15 variables, was from 1 to 3 hours, depending on the case.

7.2 Limitations

7.2.1 Limitations of the energy modelling

Due to the simplifications made in the energy model, there is a series of limitations that need to be considered before using the model.

The model does not consider the effect of thermally unconditioned areas within the building. However, if this is applied, the model would lose the applicability in other residential buildings, as the model should be especially designed for each specific building.

When it comes to the location being tested, the energy model has only been validated for Gothenburg weather conditions. As well, due to the chosen location for the project, only heating has been taken into consideration. As a future development, it would be interesting to test the model in other climates – both colder and warmer – to validate the model.

One of the aspects that have not been taken into consideration is the effect of thermal bridges. This would be interesting to study further. However, there would be a need for a thorough study on the specific buildings to test how much this would influence the system and how retrofitting would impact in the thermal bridge reduction.

7.2.2 Limitations of the optimization

As it was already stated, the retrofitting data is a set of discrete values that are adapted to a polynomic function for the optimization process. The consequence of using this technique is that the obtained results are not matching with the real data. Thus, there is a need for postprocessing the results for adjusting the values to real commercial data.

For the sake of time efficiency, the selected optimization method looks for local minima. This implies that the initial guess has an impact on the solution. A method for distributing the initial guess has been developed, distributing equally insulation thickness in all the walls and keeping the original windows. In all the scenarios explored in the case study, only one of them gave a result which was not satisfactory.

When it comes to the windows, there are two limitations: the first one would be the fact that the g-value and the frame factor are kept constant. The second one lies in the fact that all windows are treated as one building element. Even though there was a reasoning behind this decision, which can be found in section 5.3, this can be considered as a limitation.

Lastly, it must be stated that the choice of the insulation for each wall should be selected before the optimization is run. During the optimization, only one type of insulation is considered.

7.3 Future developments

Taking into consideration the limitations of the model, the current context of building retrofitting and the potential of the developed tool, a set of future developments can be stated.

Firstly, the energy modelling could be developed to include the possibility to add thermally unconditioned zones such as storage rooms or basement, which might not be heated to a thermal comfort temperature.

As well, thermal bridge modelling could be interesting to study further their effects and how they can be reduced by adding insulation and replacing the windows. Nevertheless, as it was mentioned before, the data that needs to be known about the building would increase tremendously, as in-depth studies should be carried out.

The model could be tested and validated in other climate zones since the calculations are generic and not limited to cold climates.

When it comes to data input in the program, the area of each building element should be introduced via the Excel sheet. The program would be more visual if a CAD tool was introduced for introducing the geometrical data.

Regarding the data provided after the optimization, some other indicators could be added, such as the Net Present Value, the lost floor area with internal insulation and the saved CO_2.

As a following step, as well, a more holistic approach towards energy savings in buildings could be taken. Aspects like the consumption of electric devices, as well as local production of energy with efficient boilers or photovoltaic panels, could be introduced.

7.4 Conclusions

The original goal of this Master Thesis was creating a simple yet accurate heating demand simulation model and creating a detailed and time-efficient optimization tool for retrofitting existing residential buildings.

It can be said that the selected energy modelling – ISO 52016-1:2017 – performs perfectly well according to the goals. The building elements are considered separately, which is ideal for a retrofitting scenario like the one that is considered. Not only that but the fact that the thermal mass of every opaque element is shifted according to the structure of the wall adds more accuracy to the modelling.

Besides, the hourly time steps allow detailed simulations that takes into account the effect of solar radiation and exterior temperature, as well as the thermal inertia of every element. Furthermore, the way of calculating the energy demand results in a time-efficient energy model.

When it comes to the optimization strategy, the Matlab resources in optimization have been used, which resulted in the adaptation of the input data. Continuous functions built from discrete data have been fed into the system with satisfactory results. However, the need for postprocessing the data and the fact that the found optimal is not the global solution opens the door to considering other optimization methods.

Taking into consideration both the energy modelling and the optimization, the developed tool is suitable for situations in which fast and detailed space heating simulations are needed. It is also suitable for deciding which retrofitting measures must be used in an existing building, considering their price and their effectiveness.

All in all, it can be stated that the original goal of the project has been achieved and there is potential in this model for further development.

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Appendix A - Usage factors for residential buildings

The following factors are extracted from ISO 17772-1:2017 [53].

Table 38. Usage factors for one-, two- and multi-dwelling buildings, by hour and day of the week.

h	Occupants weekdays	Occupants weekends	Appliances (all week)
1	1	1	0.5
2	1	1	0.5
3	1	1	0.5
4	1	1	0.5
5	1	1	0.5
6	1	1	0.5
7	0.5	0.8	0.5
8	0.5	0.8	0.7
9	0.5	0.8	0.7
10	0.1	0.8	0.5
11	0.1	0.8	0.5
12	0.1	0.8	0.6
13	0.1	0.8	0.6
14	0.2	0.8	0.6
15	0.2	0.8	0.6
16	0.2	0.8	0.5
17	0.5	0.8	0.5
18	0.5	0.8	0.7
19	0.5	0.8	0.7
20	0.8	0.8	0.8
21	0.8	0.8	0.8
22	0.8	0.8	0.8
23	1	1	0.6
24	1	1	0.6

Appendix B - Summary of final equations introduced in Matlab for a time step t

- Energy balance thermal zone:

$$\left[\frac{C_{int}}{\Delta t} + \sum_{k=1}^{elements} \left(A_k \cdot h_{int\,conv,k}\right) + H_{vent;t} + H_{tb}\right] \cdot \theta_{air;t} - \sum_{k=1}^{elements} \left(A_k \cdot h_{int\,conv,k} \cdot \theta_{surf\,k;t}\right) = \frac{C_i}{\Delta t} \cdot \theta_{air;t-1} + H_{vent;t} \cdot \theta_{supply;t} + f_{int} \cdot \Phi_{int} + f_{sol} \cdot \Phi_{sol} + f_H \cdot \Phi_H \tag{59}$$

- External surface node (node 1), floor:

$$A_{floor} \cdot \left(\left(h_1 + \frac{1}{R_{ground\,virtual}}\right) \cdot \theta_{1;t} - h_1 \cdot \theta_{2;t}\right) = A_{floor} \cdot \frac{1}{R_{ground\,virtual}} \cdot \theta_{ext;t} \tag{60}$$

- Energy balance intermediate node 2, floor:

$$A_{floor} \cdot \left(-h_1 \cdot \theta_{1;t} + \left[\frac{\kappa_{gr}}{\Delta t} + h_2 + h_1\right] \cdot \theta_{2;t} - h_2 \cdot \theta_{3;t}\right) = A_{floor} \cdot \left(\frac{\kappa_{gr}}{\Delta t} \cdot \theta_{2;t-1}\right) \tag{61}$$

- Energy balance intermediate node 3, floor:

$$A_{floor} \cdot \left(-h_2 \cdot \theta_{2;t} + \left[\frac{\kappa_3}{\Delta t} + h_3 + h_2\right] \cdot \theta_{3;t} - h_3 \cdot \theta_{4;t}\right) = A_{floor} \cdot \left(\frac{\kappa_3}{\Delta t} \cdot \theta_{3;t-1}\right) \tag{62}$$

- Energy balance intermediate node 4, floor:

$$A_{floor} \cdot \left(-h_3 \cdot \theta_{3;t} + \left[\frac{\kappa_4}{\Delta t} + h_4 + h_3\right] \cdot \theta_{4;t} - h_4 \cdot \theta_{5;t}\right) = A_{floor} \cdot \left(\frac{\kappa_4}{\Delta t} \cdot \theta_{4;t-1}\right) \tag{63}$$

- Energy balance internal surface node (node 5), floor:

$$A_{floor} \cdot \left(-\left(h_4 \cdot \theta_{4;t}\right) + \left[\frac{\kappa_5}{\Delta t} + h_{int\,conv} + h_{int\,rad} \cdot \sum_{\substack{j=1\\ j\neq k}}^{elements} \left(\frac{A_j}{A_{tot}}\right) + h_4\right] \cdot \theta_{5;t} \right.$$

$$\left. -h_{int\,conv} \cdot \theta_{air;t} - \sum_{\substack{j=1\\ j\neq k}}^{elements} \left(\frac{A_j}{A_{tot}} \cdot h_{int\,rad} \cdot \theta_{last\,node,j;t}\right) \right) \tag{64}$$

$$= A_{floor} \cdot \left(\frac{\kappa_5}{\Delta t} \cdot \theta_{5;t-1} + \frac{1}{A_{tot}}\left[(1-f_{int}) \cdot \Phi_{int} + (1-f_{sol}) \cdot \Phi_{sol} + (1-f_H) \cdot \Phi_H\right]\right)$$

- External surface node (node 1), roof and walls:

$$A_{element} \cdot \left(\left[\frac{\kappa_1}{\Delta t} + h_{ext\,conv} + h_{ext\,rad} + h_1\right] \cdot \theta_{1;t} - \left(h_1 \cdot \theta_{2;t}\right)\right) = A_{element} \cdot \left(\frac{\kappa_1}{\Delta t} \cdot \theta_{1;t-1} + (h_{ext\,conv} + h_{ext\,rad}) \cdot \theta_{ext;t} + a_{sol} \cdot \left(I_{dif;t} + I_{dir;t}\right) - \Phi_{sky;t}\right) \tag{65}$$

- Energy balance intermediate nodes 2, 3 and 4, roof and walls:

$$A_{element} \cdot \left(-h_{n-1} \cdot \theta_{n-1;t} + \left[\frac{\kappa_n}{\Delta t} + h_n + h_{n-1}\right] \cdot \theta_{n;t} - h_n \cdot \theta_{n+1;t}\right) = A_{element} \cdot \left(\frac{\kappa_n}{\Delta t} \cdot \theta_{n;t-1}\right) \tag{66}$$

- Energy balance internal surface (node 5), roof and walls

$$A_{element} \cdot \left(-\left(h_4 \cdot \theta_{4;t}\right) + \left[\frac{\kappa_5}{\Delta t} + h_{int\ conv} + h_{int\ rad} \cdot \sum_{\substack{j=1 \\ j \neq k}}^{elements} \left(\frac{A_j}{A_{tot}}\right) + h_4 \right] \cdot \theta_{5;t} \right.$$

$$\left. -h_{int\ conv} \cdot \theta_{air;t} - \sum_{\substack{j=1 \\ j \neq k}}^{elements} \left(\frac{A_j}{A_{tot}} \cdot h_{int\ rad} \cdot \theta_{last\ node,j;t}\right) \right) \tag{67}$$

$$= A_{element} \cdot \left(\frac{\kappa_5}{\Delta t} \cdot \theta_{5;t-1} + \frac{1}{A_{tot}} \left[(1 - f_{int}) \cdot \Phi_{int} + (1 - f_{sol}) \cdot \Phi_{sol} + (1 - f_H) \cdot \Phi_H \right] \right)$$

- External surface node windows (node 1):

$$A_{element} \cdot \left([h_{ext\ conv} + h_{ext\ rad} + h_1] \cdot \theta_{1;t} - \left(h_1 \cdot \theta_{2;t}\right) \right) = A_{element} \cdot \left((h_{ext\ conv} + h_{ext\ rad}) \cdot \theta_{ext;t} - \Phi_{sky;t} \right) \tag{68}$$

- Energy balance internal surface node windows (node 2):

$$A_{element} \cdot \left(-\left(h_1 \cdot \theta_{1;t}\right) + \left[h_{int\ conv} + h_{int\ rad} \cdot \sum_{\substack{j=1 \\ j \neq k}}^{elements} \left(\frac{A_j}{A_{tot}}\right) + h_1 \right] \cdot \theta_{2;t} \right.$$

$$\left. -h_{int\ conv} \cdot \theta_{air;t} - \sum_{\substack{j=1 \\ j \neq k}}^{elements} \left(\frac{A_j}{A_{tot}} \cdot h_{int\ rad} \cdot \theta_{last\ node,j;t}\right) \right) \tag{69}$$

$$= A_{element} \cdot \left(\frac{1}{A_{tot}} \left[(1 - f_{int}) \cdot \Phi_{int} + (1 - f_{sol}) \cdot \Phi_{sol} + (1 - f_{HC}) \cdot \Phi_H \right] \right)$$

Appendix C - Summary of conventional coefficients and factors

- Surface heat transfer coefficients. Data from ISO 13789:2017 [52].

Surface heat transfer coefficient (W/m^2·K)	Upwards	Horizontal	Downwards
Internal convective surface coefficient, $h_{int\ conv}$	5.0	2.5	0.7
Internal radiative surface coefficient, $h_{int\ rad}$	5.13	5.13	5.13
External convective surface coefficient, $h_{ext\ conv}$	20	20	20
External radiative surface coefficient, $h_{ext\ rad}$	4.14	4.14	4.14

- Surface resistances. Data from ISO 6946:2017 [32].

Surface resistances (m^2·K/ W)	Upwards	Horizontal	Downwards
Internal surface resistance, R_{si}	0.10	0.13	0.17
External surface resistance, R_{se}	0.04	0.04	0.04

- Value of κ_m according to type of construction. Data from ISO 52016-1:2017 [28].

Class	K_m J/(m^2·K)	Description of the class
Very light	50 000	No mass components other than plastic board and/or wood siding, or similar.
Light	75 000	No mass components other than 5-10 cm of lightweight brick or concrete, or similar.
Medium	110 000	No mass components other than, either 10-20 cm of lightweight brick or concrete, or less than 7 cm of solid brick or heavy weigh concrete, or similar.
Heavy	175 000	7-12 cm of solid brick or heavy weight concrete, or similar.
Very heavy	250 000	>12 cm of solid brick or heavy weight concrete, or similar.

- Suggested convection factors. Data from ISO 52016-1:2017 [28].

Convection factor	Suggested value
f_{int}	0.40
f_{sol}	0.10
f_H	0.40

- Internal gains per square meter on residential buildings, by type of gain. Data from ISO 17772-1:2017 [53]

Internal gains (W/m^2)	One-, two-dwelling apartments	Multi-dwelling apartments
Occupants	2.8	4.2
Appliances	2.4	3.0

- Areal heat capacity of the fixed ground element for a 0.5 m thick ground layer. Data from ISO 13370:2017 [54].

Type of soil	$\boldsymbol{K_{gr}}$ **J/(m²·K)**
Clay or silt	$1.5 \cdot 10^6$
Sand or gravel	$1.0 \cdot 10^6$
Homogeneous rock	$1.0 \cdot 10^6$

- Default values for solar absorption coefficients according to the color of the external surface. Data from ISO 52016-1:2017 [28].

Type of surface	$\mathbf{a_{sol}}$
Light color	0.3
Intermediate color	0.6
Dark color	0.9

Appendix D - Summary of calculation of properties for different building elements

D.1 Walls

Areal heat capacity

Depending on the mass distribution:

Mass concentrated at internal side	$\kappa_5 = \kappa_m$ $\kappa_2 = \kappa_3 = \kappa_4 = \kappa_5 = 0$
Mass concentrated at external side	$\kappa_1 = \kappa_m$ $\kappa_1 = \kappa_2 = \kappa_3 = \kappa_4 = 0$
Mass divided over interior and exterior	$\kappa_1 = \kappa_5 = \frac{\kappa_m}{2}$ $\kappa_2 = \kappa_3 = \kappa_4 = 0$
Equally distributed mass	$\kappa_1 = \kappa_5 = \frac{\kappa_m}{8}$ $\kappa_2 = \kappa_3 = \kappa_4 = \frac{\kappa_m}{4}$
Mass concentrated inside	$\kappa_3 = \kappa_m$ $\kappa_1 = \kappa_2 = \kappa_4 = \kappa_5 = 0$

Conductance between nodes and thermal resistance

Conductance between nodes:

$$h_1 = h_4 = \frac{6}{R_k} \qquad h_2 = h_3 = \frac{3}{R_k}$$

Thermal resistance:

$$R_k = \frac{1}{U_k} - R_{si} - R_{se} \quad \text{or} \quad R_k = \sum_{layers} R_{layer}$$

D.2 Elements in contact with the ground

Areal heat capacity

For all classes:

$$\kappa_1 = 0 \qquad \kappa_2 = \kappa_{gr}$$

Depending on the mass distribution:

Mass concentrated at internal side	$\kappa_5 = \kappa_m$ $\kappa_3 = \kappa_4 = \kappa_5 = 0$
Mass concentrated at external side	$\kappa_3 = \kappa_m$ $\kappa_4 = \kappa_5 = 0$
Mass divided over interior and exterior	$\kappa_3 = \kappa_5 = \frac{\kappa_m}{2}$ $\kappa_4 = 0$
Equally distributed mass	$\kappa_3 = \kappa_5 = \frac{\kappa_m}{4}$ $\kappa_3 = \frac{\kappa_m}{2}$
Mass concentrated inside	$\kappa_4 = \kappa_m$ $\kappa_3 = \kappa_5 = 0$

Conductance between nodes and thermal resistance

Conductance between nodes:

$$h_4 = \frac{4}{R_k} \qquad h_3 = \frac{2}{R_k}$$

$$h_2 = \frac{1}{\left(\frac{R_k}{4} + \frac{R_{ground}}{2}\right)} \qquad h_1 = \frac{2}{R_{ground}}$$

where R_{ground} is the thermal resistance of 0.5 m of ground, in $(m^2 \cdot K)/W$, and calculated as:

$$R_{ground} = 0.5/\lambda_{ground}$$

The thermal conductivity of the ground depends on the type of soil. This value is given in EN ISO 13370:2017 [54] and it is shown in Table 16.

Table 39. Thermal conductivity of the ground.

Type of soil	λ_{ground} **W/(m·K)**
Clay or silt	1.5
Sand or gravel	2.0
Homogeneous rock	3.5

Note that in the case of the elements in contact with the ground, the thermal resistance of the building element, R_k, is calculated differently than in the other building elements, as shown in Equation (40).

$$R_k = \frac{1}{U_k} - R_{si}$$

The U-value for the elements in contact with the ground is not an input, unlike the other elements. The calculations for this variable are based in ISO 13370:2017 [54]. The case of a *heated basement* will be taken, i.e. part of the habitable area is located below ground level, as shown in Figure 6.

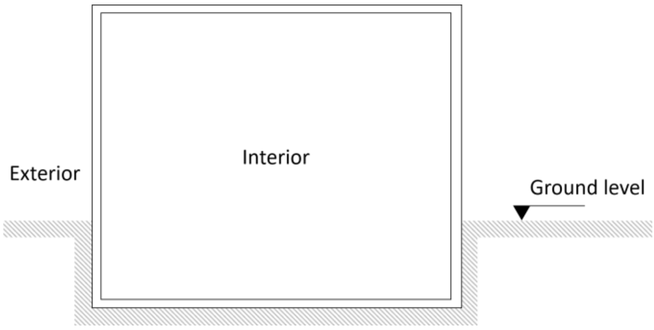

Figure 22. Heated basement.

The reason behind this decision is that the equations for the *slab-on-ground* floor are obtained in case the depth of the basement below ground level, z, is zero.

In this case, there is a distinction between the floor of the basement and the wall of the basement.

The U-value for the basement floor (indicated as *bf* in the subscript) can be calculated according to Equation (41) if the basement floor is poorly or moderately insulated, or according to Equation (42) in case the floor is well insulated.

$$U_{bf} = \frac{2 \cdot \lambda_{ground}}{\pi \cdot B + d_{floor} + 0.5 \cdot z} \cdot \ln\left(\frac{\pi \cdot B}{d_{floor} + 0.5 \cdot z} + 1\right) \qquad \text{if } d_{floor} + 0.5 \cdot z < B$$

$$U_{bf} = \frac{\lambda_{ground}}{0.457 \cdot B + d_{floor} + 0.5 \cdot z} \qquad \text{if } d_{floor} + 0.5 \cdot z \geq B$$

Where the geometrical factor *B* is calculated as

$$B = \frac{A_{floor}}{0.5 \cdot Perimeter_{floor}}$$

The total equivalent thickness, d_{floor}, is calculated with the formula shown in Equation (44), provided in ISO 13370:2017.

$$d_{floor} = d_{walls} + \lambda_{ground} \cdot (R_{si} + R_{floor} + R_{se})$$

Regarding the basement walls (*bw* in the subscript), the U-value is calculated according to Equation (45) or Equation (46), depending on the value of the total equivalent thickness for the basement walls, d_{bw}.

$$U_{k,bw} = \frac{2 \cdot \lambda_{ground}}{\pi \cdot z} \cdot \left(1 + \frac{0.5 \cdot d_{floor}}{d_{floor} + z}\right) \cdot \ln\left(\frac{z}{d_{bw}} + 1\right) \qquad \text{if } d_{floor} \leq d_{bw}$$

$$U_{k,bw} = \frac{2 \cdot \lambda_{ground}}{\pi \cdot z} \cdot \left(1 + \frac{0.5 \cdot d_{bw}}{d_{bw} + z}\right) \cdot \ln\left(\frac{z}{d_{bw}} + 1\right) \qquad \text{if } d_{floor} > d_{bw}$$

The total equivalent thickness for the basement walls, d_{bw}, is calculated with the formula shown in Equation (47)(44), provided in ISO 13370:2017.

$$d_{bw} = \lambda_{ground} \cdot (R_{si} + R_{bw} + R_{se})$$

D.3 Glazed elements

Areal heat capacity

Not considered: $\kappa_n = 0$

Conductance between nodes and thermal resistance

Conductance between nodes:

$$h_1 = \frac{1}{R_k}$$

Thermal resistance:

$$R_k = \frac{1}{U_k} - R_{si} - R_{se}$$