Hygrothermal Analysis of Retrofitted Buildings in the Campus of Lund University

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Master thesis in Energy-efficient and Environmental Buildings | Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

Master Programme in Energy-efficient and Environmental Building Design

This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Keywords: Retrofit, Interior Insulation, Hygrothermal, Energy Simulations, Life Cycle Cost, Life Cycle Assessment

Thesis: EEBD - 07 / 16

Abstract

As climate change have become generally accepted as a potential problem, reducing the greenhouse gas emissions and global energy demand has become an important research topic. This have led to an increased interest towards the retrofitting of the existing building stock, including cultural protected buildings. Due to the cultural protection, carrying out major alteration such as exterior wall retrofits are often not possible, leaving interior retrofitting as the only option. Previous studies have however shown that interior retrofitting poses great risks with respect the hygrothermal performance. This study focused on assessing the long term performance of various energy retrofitting measures for the exterior wall and roof constructions with respect to energy- and moisture performance, window replacement was not included. Carried out for two protected buildings in the campus of Lund University, and the adaptability of the retrofitted measures towards the future climate conditions, simulated until year 2100. The economic- and environmental feasibility of the retrofitting measures was furthermore determined through LCC and LCA. Results showed the smart vapour retarder assemblies would outperform both the capillary active as well as the traditional assemblies using PE-foil, with respect to the hygrothermal performance. However, the water repellent coating showed to be vital for any of the wall assemblies to problem free. A potential reduction of the heating demand by 20-30% was shown for the retrofitted walls, while only 5% for the retrofitted roof constructions. The retrofitting measures were shown to be economic infeasible, while the wall measures were shown to be environmental feasible.

Acknowledgements

The master thesis was carried out in collaboration with the Akademiska Hus, and I would therefore like to show my gratitude to Akademiska Hus, for contributing to this project by providing the drawing material, descriptions as well as existing energy calculations. From where I would like to give a special thanks to Li Lövehed and Tina Andersson, who were my contact persons at Akademiska Hus.

I would like to thank Bahare M. Kermani for her support and help. Her feedback during the simulation process has been of great importance for my thesis work.

I would like to give a special thanks to my girlfriend Noora, who has supported and motivated me during this hard period. I would also like to thank my family and classmates, who have provided support, motivation, as well as raised critical questions regarding the content of the project.

Finally, I would like to show my immense gratitude to my supervisor Vahid M. Nik for his support and help. His knowledge, guidance and encouragement have been of great importance for me during the thesis work, which have also helped me to exceed my own expectations for the project.

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1 List of terms, abbreviations and notations

1.1 Terminology

Fraction Schedule (Schedule Compact): uses fractional values to specify the properties of occupant, heating, cooling, equipment, lighting and mechanical ventilation schedules, by assigning a fraction value for each hour.

Heat Recovery: means to exchange heat or cold between the exhaust air and the supply air to pre-heat or pre-cool the supply air before it reaches the heating-/ cooling coils in the ventilation system, which in turn helps to save energy for heating and cooling.

Hygrothermal: relates to the flow of both moisture and heat through the building envelope.

Infiltration Rate: is the speed at which outside air enters the building through the building envelope, measured in litres per second per square meter floor area.

Interior Heat Gains: is used to specify the sensible and latent heat which is emitted within a zone from equipment, lighting and occupants, which in turn will affect the heating and cooling demand of the building.

Interstitial Condensation: occurs within the building envelope when the warm moist indoor air penetrates through the building envelope and reaches the dew point, at which it will condensate into liquid water inside the construction.
Setpoint Temperature: is used to specify the ideal temperature in a zone when heat and cooling are required during the occupied hours.

Lighting Power Density: presents the energy load for the electrical lighting in a zone, measured in Watts per square meter for the purpose of this study.

Occupancy Density: is used to define the number of people in a zone, measured in people per square meter, which is the unit accepted by the simulation software.

Setback Temperature: is used to specify the ideal temperature in a zone during the unoccupied hours.

Thermal Bridge: is a definition of an area with considerably higher heat transfer than the surrounding building components such as junctions between roof and exterior wall or around windows and doors.

1.2 Abbreviations

AAC	Autoclaved aerated concrete
AC/H	Air Changes per hour
AHU	Air handling unit
CaSi	Calcium silicate
CoP	Coefficient of performance

EPS	Expanded polystyrene
HR	Heat recovery
HVAC	Heating, ventilation, and air-conditioning
IDF	Input date file
LCA	Life cycle assessment
LCC	Life cycle cost
LoE	Low thermal emissivity
LPD	Lighting power density
MDF	Medium density fibreboard
NPV	Net-present-value
OSB	Oriented strand board
RH	Relative humidity [%]
SFP	Specific fan power [kW/(m3/s)]
SVR	Smart vapour retarder
VAV	Variable air volume
VIP	Vacuum insulating panel
WWR	Window to wall ratio [%]
XPS	Extruded polystyrene

1.3 Notation

·	Multiplication symbol
°	Degrees
ΔT	Temperature difference [K]
λ	Heat Conductivity [W/m·K]
ρ	Density [kg/m^3]
Ψ	Linear thermal transmittance [W/m·K]
A_1	Future worth after one year [SEK]
C	Celsius
C_p	Specific heat capacity, at constant pressure [J/(kg·K)]
F	Future worth [SEK]
g_r	Growth rate [%]
SHGC	Solar heat gain coefficient [%]
i	Interest rate [%]
K	Degree Kelvin
kWh	Kilowatt-hour
L_n	Length of the junction part n [m]
N	Number of compounding periods
P	Present worth [SEK]
q_n	Total heat loss through the junction part n [W/m]
q_{tot}	Total heat loss through the entire junction [W/m]
R-value	Thermal Resistance [m^{2}K/W]
S_d	Vapour diffusion thickness [m]
T_{sol}	Solar transmittance [%]
T_{vis}	Visible transmittance [%]
U-value	Thermal Conductance [W/m^2·K]
W	Watt

2 Introduction

In recent years' climate change has become generally accepted as a potential problem. As a response to this problem a large number of politicians, companies as well as individuals worldwide, have shown incentive towards sustainability and a greener future for the planet. A failure to reduce the energy use and greenhouse gas emissions could have catastrophic consequences. [1] [2] [3] As a result of the increased incentive towards sustainability, several demands for energy reducing measure as well as preparation work towards probable future climate conditions have been placed upon the building sector. Preparation work which includes retrofitting of the older, inefficient part of the building stock, as this part of the building stock yield great potential towards energy savings. [4] Despite the energy saving potential and good reasoning, retrofitting older buildings may lead to severe moisture problems, as a result of a change in the hygrothermal behaviour of the constructions [5] [6]. In addition to the risk of moisture problems after a retrofitting project, it has also been predicted that due climate change, certain areas may experience more precipitation and extreme weather events in the future. An increase in precipitation and extreme weather events poses an increased risk for the moisture performance of buildings. [7] It has been predicted that the Northern part of Sweden will experience less days with extreme cold temperature during the winter. The Southern part of Sweden will experience more days with high temperatures during the summer as well as more tropical night temperatures. [8] In an attempt to prevent moisture problems related to retrofitting of older buildings, several innovative solutions have been developed. This study aims to shed light on the energy- and moisture performance of some of these solutions, with respect to both the current- and future climate conditions.

2.1 Objectives

The main objective of this study is to assess the long term performance of various energy retrofitting measures for the exterior wall and roof constructions with respect to energy efficiency and moisture performance, for two protected buildings in the campus of Lund University in southern Sweden. The second objective is to determine the feasibility of the approved retrofitting measures, with respect to Life Cycle Assessment and Life Cycle Cost. The conclusions drawn from this study are intended to assist designers working with energy retrofitting of culturally protected buildings, to assure the long term performance of the building with respect to energy efficiency and moisture safety as well as to determine project feasibility.

2.2 Scope

This study intent to investigate the hygrothermal performance of selected construction parts as well as the energy performance of two buildings, before and after retrofitting. The focus will primarily be on reducing the energy demand for space heating and increasing the moisture safety, when additional thermal insulation is added on the interior side of existing walls. In addition to the investigation of the exterior walls, also the roof constructions will be subject to energy retrofit. In contrast to the wall constructions, less focus will be placed on the roof constructions in comparison, as the existing roof constructions were renovated quite recent and were therefore considered to be in relatively good condition.

The long term performance for each of the retrofitting measures as well as the two buildings as a whole will be investigated by considering several scenarios for future climate conditions. Further investigations will be carried out with respect to the economic and the environmental feasibility of the assemblies, through Life Cycle Cost and Life Cycle Assessment, where energy- and material usage will be accounted for.

2.3 Research questions

The results of this study aim to answer to the following research questions:

1) The long term hygrothermal performance of the retrofitted construction parts such as exterior walls and roofs, focusing on their moisture safety and desired thermal performance.
2) Effectiveness and robustness of the retrofitting measures for improved thermal performance.
3) Impacts of climate change on the hygrothermal and thermal performance of buildings in the campus of Lund University.
4) The economic and environmental feasibility of the retrofitting measures.
5) To apply the retrofitting measures to multiple buildings with similar climate conditions and achieve satisfactory results.

2.4 Limitations

This study was carried out entirely based on the numerical simulations regarding the long term performance of the building. Field measurements were however provided by Akademiska Hus, these were used to validate the simulation results for the current climate simulations. Another limitation was that only the exterior wall- and roof constructions were studied. An additional limitation was that the retrofitting measures investigated in this study were applied to two school buildings from the 1960's. As a result, the conclusions drawn from this study may not be applicable to other building types with different load factors, or buildings which are located in different climatic regions. A limitation within energy performance study was that only the energy demand for space heating- and cooling was taken into consideration during the building simulations. The energy demand for electricity, domestic hot water, equipment as well as the HVAC unit, was not taken into consideration. These factors were specified in the given material and their quantities will be stated in the methodology section. The cooling demand, however, was not included in the LCA and LCC, as no information regarding the cooling system serving the two buildings were provided. The final limitation within this study was that the hygrothermal simulations were carried out only in one dimension using WUFI 1D. Moisture accumulation in the junctions between envelope parts (two dimensional simulations) were not assessed in this study.

3 Overview of the problem

3.1 Climate change and global future overlook

Reducing the greenhouse gas emissions and global energy demand has been an important research topic during recent years. Such a reduction is considered as the most effective strategy to reduce the pace and consequently the impacts of climate change, which is predicted to result in shifting weather patterns on a global scale. Such a shift can result in a number of global scale problems in a near future, hereunder shrinking ice caps at the poles, rising sea levels, heat waves, droughts, wildfires, extreme precipitation, winter precipitation, hurricanes, tornadoes, floods, warmer and more acidic oceans, loss of biodiversity, as well as spreading of nuisance animals and insects currently limited to the tropical regions. [1] [2] [3] The European Environment Agency (EEA) documented in 2011 how the number of natural disasters have increased in the period 1998-2009, which among others included storms, forest fires, droughts, and floods. The study by the EEA showed that during this period, these natural disasters was responsible for almost 100000 deaths as well as material damages for around €150 billion. [9] The capital area of Denmark experienced its worst rain fall in almost 60 years on July 2nd 2011 [10]. Most of the capital area measured a rain fall between 30 and 90 mm during the meteorological day [11] [12], with a local peak of 135 mm measured in the Copenhagen botanical garden [12] [10]. The large amount of rain resulted in flooded streets, railway tracks, basements and low laying apartments. Due to the flooding of streets and railway tracks, a few highway areas were closed and several train routes were discontinued for up to one week. The flooding of basements and low laying apartments resulted in more than 90000 damage reports with a total cost of approximately 4.88 billion DKK. [10] [11] And as recent as in June 2016 Denmark experienced several heavy rain falls, where some areas received a full month's rain fall in just a few hours [13] [14] [15] [16]. And on June 23rd the heavy rain falls broke a 23-year-old record, where the island of Ærø in the Southern part of Denmark experienced a rain intensity of 5.5 mm per minute. The 2016 record was approximately 25% higher than the previously measured record from 1993. [16]

In recent years also Sweden have experienced a number of extreme weather events, as the country have been hit by several floods. Back in the summer of 2012 Sweden experienced major floods in several areas in the Southern part of the country after a night with heavy rain falls. Many houses needed to be pumped free from water, and emergency dams were constructed to avoid further damages. [17] And in 2014 Sweden experienced yet another flooding in the Southern part of the country caused by heavy rain falls, which resulted in large amount of flood related damages. Four insurance companies reported that they each had received between 400-980 reports concerning flooding damages to houses, holiday homes, commercial buildings as well as cars. The insurance company If estimated that they would pay back 40-50 million SEK as compensation, while the insurance company Trygg-Hansa estimated the average cost for each of the 500 reported cases to be between 50000 and 500000 SEK. [18] According to Swedish Meteorological and Hydrological Institute (SMHI), the Southern part of Sweden as well as the North-Western part is likely to experience more frequent floods in the future, caused by lakes and rivers running over due to heavy rain falls. The North-Eastern part of Sweden as well as parts of central Sweden on the other hand, will experience less frequent floods. [7]

Evidence show that human activities and the greenhouse gas emissions associated with them are the primary cause of the climate change, due to activities such as fossil fuel burning, deforesting, industrial- and agricultural processes. The greenhouse gasses act sort of like an insulator around the planet, trapping heat energy in the atmosphere. [19] [2] Upon entry, the direct sunlight is allowed to pass through the atmosphere where the short-wave radiation will heat up the surface of the earth, and as this happens the long-wave radiation is reflected back towards the atmosphere. The long-wave radiation is then during its return through the atmosphere absorbed by the greenhouse gasses, as a result, less heat energy is allowed to leave the atmosphere, resulting in warming of the atmosphere. [20] The signs of atmospheric warming are already visible today, as ice caps and glaciers are continuing to retreat as well as snow and ice covers on land, lakes and river start to melt earlier. [1] [3]

Industrial development around the world and the environmental impacts associated with it have been predicted by the International Energy Agency (IEA). In the IEA World Energy Outlook 2015 report it is stated that an energy increase by 1/3 is likely to have occurred already by 2040, primarily driven by Asia, the Middle East and Africa. China and India have been predicted to play a major role in the future energy- and emissions scenarios, granted that both countries are expected to experience large growth within several sectors. Predictions regarding China's energy demand, suggest that they by 2040 will reach twice the amount of the United States, and that they will surpass both Europe and the United States in oil and gas consumption. In contrast to China's growing demand for oil and gas, China has also been predicted to surpass Europe and the United States in renewables. As China in recent years have invested in large scale application of wind, solar, hydro and nuclear power, and it has been predicted that China's share of renewables will continue to grow in the future. In additional to China's development, also India have been carefully observed, as it has been predicted that their development will be followed by a greatly increased demand for coal and oil, making them the largest importer of coal already by 2020. At present time, around 1.2 billion people live in India, however, up to 80% of them do not have access to electricity. As a result, it has been predicted that India's' electricity demand will experience a great increase in the coming years, as they expand their power sector to supply electricity to this group of people. In the same way as with China, also India have invested in large scale application of hydro, nuclear, wind, and solar power. Where the latter two are considered to have high potential in India. [21]

3.2 Energy figures for the building sector

As a consequence of the global desire to reduce the energy use, each sector, hereunder also the building sector, has been faced with demands for energy reducing measure. A report from 2009 by the United Nations Environment Programme (UNEP) state that the building sector yields a great potential towards a global energy reduction, granted that the building sector on a global scale accounts for 40% of energy use, 25% of the water consumption, as well as 33% of the greenhouse gas emissions. [4] Further evidence show that the residential and commercial buildings account for 60% of the global electricity use [22]. Most of these figures are the same for both Europe and the United States. In the United States the building sector accounts for around 41% of the total energy consumption [23] [24] and 40% of the CO_2 emissions [23], while in Europe the building sector accounts for around 40% of the total energy consumption and 36% of the CO_2 emissions [25]. The European Commission state that 1/3 of the European building stock consist of inefficient buildings which are more than

50 years old. [25] A survey by BSRIA found that 6-7% of the European residential building stock and 14% of the commercial building stock were dated after year 2000. [26] The large number of inefficient buildings in Europe creates a large potential for energy reducing measures within the European building sector. The analysis of the European retrofitting potential estimated that a retrofit of the buildings +50 years of age will result in a reduction of approximately 5% of Europe's total energy use and CO_2 emissions. [25]

A bit closer to home, the Swedish Energy Agency stated in 2005 that around 38% of the total energy use as well as a little less than 20% of the total CO_2 emissions in Sweden, came from residential and non-residential buildings. The relatively low emission of CO_2 is due to Sweden's nuclear power plants, which account for approximately 40% of electricity demand. Although the nuclear power plants are low in CO_2 emissions, electricity production through nuclear power comes with its own hazards. The Swedish Energy Agency also stated that within the Swedish building sector, 41% of the electricity demand was used for operational electricity, 27% for household electricity, and the remaining 32% for electric heating. [27] In the same way as with the retrofitting potential within the building stock on a European scale, the Swedish building sector also yield a great potential towards retrofitting. Evidence by the Swedish Environental Protection Agency (Naturvårdsverket) suggest that about 2% of the Swedish building stock or 67000 building are considered as listed buildings. [28] [29] A large portion of these buildings are likely to have a thermal performance which are considerably worse than today standards [28].

With regards to Sweden's future energy goals, the 2013 IEA Countries Review state that Sweden is by the International Energy Agency viewed as one of the leading member countries towards energy reductions and renewable energy, already aiming higher than the European 2020 energy goals [30].

3.3 Moisture problems in the Swedish building sector

Moisture is considered as one of the most common reason for damages in Swedish buildings, according to an investigation carried out by Byggkommissionen in 2002. Further investigation was carried out in 2010 by the Swedish National Board of Housing, Building and Planning, the investigation was named "BETSI". A total of 1800 buildings were investigated, including single- and multi-family residences, as well as commercial buildings. The BETSI investigation concluded that 36% of the Swedish building stock could have potential problems with moisture or mould growth. Out of all the single-family buildings investigated in BETSI, 38% showed problems, for multi-family buildings that number was around 13%, while the commercial buildings was around 11%. The investigation also showed, that the construction parts most frequently affected by moisture or mould problems were the attic and crawl space, with around 20-22% of all the investigated buildings being affected. More than that, the investigation showed a large risk for moisture or mould problems in the slab on ground and basement constructions from before 1976, with 15% and 19% respectively. [31] Moisture and mould are already today a common problem in the building sector, and it has been predicted that due to the possible shift in the weather patterns, that these figures will increase in the future, caused by events such as extreme precipitation and flooding.

3.4 Moisture induced problems in buildings

Although moisture can induce a large number of problems in the built environment, only the risk of mould growth and freeze thaw damage were assessed in this study. The risk of mould growth and freeze thaw damage were chosen due to the type of existing constructions as well as the legislation placed upon the building facades.

3.4.1 Mould growth

Mould is a type of fungus which can occur within the construction if a number of preconditions are present simultaneously [6]. Mould spores are often found in buildings, however in large quantities these spores can become a health hazard to the occupants. As a result of large quantities these spores, the occupants may develop illnesses such as allergic reactions, eczema or respiratory problems. [32] Mould growth often indicates that there is a moisture problem somewhere in the construction, such as a leaking pipe, faulty craftsmanship or interstitial condensation [33].

The preconditions for mould growth to occur are, sufficiently high relative humidity, organic nutrition, oxygen, and adequate temperatures. Evidence show that when the relative humidity is above 75 %, the mould will have good growing conditions, below this threshold, the risk of mould growth is limited. Granted that the relative humidity exceeds the threshold, the risk of mould growth will then increase along with increase in the relative humidity. [33] [6] Although good growing conditions requires a relative humidity above 75 %, it should be noted that close to 100 % relative humidity, the risk of mould growth will start to decrease. In contrast to the mould growth, the risk of rot damage starts to increase close to 100 % relative humidity. In addition to high relative humidity, mould growth requires adequate temperatures. Research have shown that the best growing conditions for mould occur at temperatures around 25-30 °C. At much higher or lower temperatures, the growth will decrease, and at temperatures above 50 °C or below 0 °C, the growth will be at a complete stop. [6] Regarding the organic nutrition, even small quantities of saw dust, dirt, soil, wet paper or even paint and adhesive residues may result in major mould growth, if the other conditions are met. Further evidence show that, mould do not appear straightaway in case of a water leakage within the construction, the correct conditions need to be present for a period of time for any mould growth will occur. The time frame depends on how well the preconditions are met. It can take from days to months. In a worst case scenario where all the preconditions are met, mould growth can appear within just a few days. To avoid mould growth in the construction, the relative humidity should be kept below the 75% threshold. This can be done by designing and carrying out moisture safe constructions, as well as by avoiding to build wet and/or dirty materials into the construction. [33] [6]

3.4.2 Freeze thaw and freeze thaw cycles

Freeze thaw, a type of structural deterioration taking place within porous façade materials like clay bricks, concrete, limestone, sandstone as well as cement render during the cold months. Deterioration due to freeze thaw occur when the façade material is exposed to freezing temperatures causing the water within the porous structure of the material to freeze, and upon freezing, the water in the pores will expand. Although structural deterioration due freeze thaw is an old problem, no exact method for determining the risk of freeze thaw exists today. [34] [35]

For freeze thaw to occur during times with freezing temperatures, the moisture content within the façade material need to be above a certain threshold, called the critical degree of saturation (S_{crit}). Evidence have shown that the threshold for modern clay bricks are reached when the moisture content in the materials is around 75-94% free water saturation (W_f). A commonly used threshold of 90 % free water saturation is often recommended when assessing the risk of freeze thaw in clay brick. [36] [37] [38] Mensinga (2009) demonstrated through the use of frost dilatometry that the commonly used threshold of 90 % was not far off, as his experiment concluded that the critical degree of saturation for modern Canadian bricks was 87 % free water saturation. In contrast Mensinga experiment also showed, that for older or historical bricks, freeze thaw could occur with moisture contents as low as 25-30% free water saturation. [38]

A Freeze Thaw Cycle occurs when the temperature within the material drops below 0 °C for a period of time and then rises above 0 °C again. The number of zero-crossings, are often considered as a good approximation for the risk of freeze thaw damages occurring. Granted that an increase in the number of zero-crossings, would also indicate an increased risk for freeze thaw damages. As a result of an increased risk for freeze thaw damages, the rate of structural deterioration should also be expected to increase, as each occurring freeze thaw cycle carries the risk of causing irreversible expansion damages to the façade material. If a freeze thaw cycle does occur, an expansion of up to 10% can be expected. Due to this expansion, the pore capacity of the façade material increases, as a result allowing the pores to contain even more water upon next freeze thaw cycle. The expansion caused by the next freeze thaw cycle will then be even larger than the first time, and so the cycling continues to expand the pores, until the façade material little by little start to crumble and fall off. The number of zero-crossings are often calculated over a long period time such as 30-50 years, as some construction may take more than just a few years to reach its moisture equilibrium. [36] [37]

Several experiments have shown that the added insulation on the interior side of the exterior wall will increase the number of freeze thaw cycles in comparison to the uninsulated exterior wall [39] [40]. Although a few sources do claim, that adding interior insulation will not majorly increase the number or severity of the freeze thaw cycles of the existing wall, as the existing wall has always been exposed to the harsh outdoor climate [38].

4 Retrofitting techniques

The term building retrofit means to modify an existing building which is already in service, through the addition of new technology and features which have become available on the market after the building was constructed. Building retrofits are typically aimed towards existing buildings which were built at a time where energy efficiency was not taken into consideration during the construction planning. As a result, making the buildings less energy efficient. [41] [42] The first building codes impacting the energy efficiency of building appeared around the 1950-60s in the Scandinavian countries. These requirements were however aimed mainly towards improved indoor comfort rather than the energy efficiency. Most countries started drawing requirements aimed towards energy efficiency in the year following the 1973/74 oil crisis, as a way to become less oil dependent. And during the 1980s and 1990s, most of the OECD (Organisation for Economic Cooperation and Development) countries had implemented energy efficiency requirements. [43] The buildings are therefore retrofitted to achieve a better energy performance and to lower the operational costs. Carrying out a building retrofit is a normally major investment, however it has often shown to be more cost effective to carry out a building retrofit of an existing building than to construct a new building. A building retrofit often involves upgrading the building envelope such as increasing the insulation in walls, roofs, and maybe floors, as well as changing the windows. In addition to upgrading the building envelope, a building retrofit often also involves upgrading the heating, ventilation and air conditioning system, water heating systems, energy control systems, lighting systems as well as to install renewable energy sources such as ground source heat pumps, solar thermal collectors or photovoltaic panel. In addition to reducing the energy demand, a building retrofit may often improve the thermal comfort as well as indoor climate, for example by increasing the amount of natural lighting or through better air quality. Other benefits may include increased building life span and value. [41] [42]

Several case studies have shown the large potential towards energy reductions through building retrofits. Liu et al. (2014) studied the energy saving potential of retrofitting eleven multi-family building in northern Sweden, by applying retrofitting measures such as wall insulation, window replacement, installing mechanical ventilation with heat recovery as well as photovoltaic panels. Their results showed that the case buildings had the potential for an energy reduction of more than 50%. [44] In another case study, Morelli et al. (2012) studied the potential of retrofitting a multi-family building from 1896 in Copenhagen to a near-zero energy building, by applying interior insulation (aerogel and VIP), replacing the windows, as well as to install a mechanical ventilation system with heat recovery. They concluded that it would be difficult to achieve the near-zero energy requirements without the use of renewable energy sources, however, his results did show an energy reduction of 68%. [45] In another near-zero energy building case study, Buvik et al. (2014) studied potential of retrofitting Brandengen Primary School in Norway from 1914, which was considered to be of historical value. The retrofitting measures included window replacement, insulating the attic and the basement walls, as well as to install a ground source heat pump. The aim of the energy retrofit was to achieve an energy reduction of 67%, which would be a reduction of the annual energy use from 200 kWh/m^2 to 68 kWh/m^2. [46] [47]

4.1 Traditional retrofitting techniques

There exist three different methods for carrying out post-insulation of exterior walls, which are as following:

- Adding exterior insulation
- Adding cavity wall insulation
- Adding interior insulation

Although only the interior insulation method was accessed in this study, all three post-insulation methods will be described in the following sections.

4.1.1 Exterior insulation

In the case of adding exterior insulation, a new layer of insulation is fixed to the exterior side of the existing wall construction through one of two construction methods, by using rigid foam insulation boards or by construction a light stud wall. After the installation of the insulation layer has been completed, the insulation will be covered by applying a render finish or by installing a cladding board. [48] [6] See Figure 1 below.

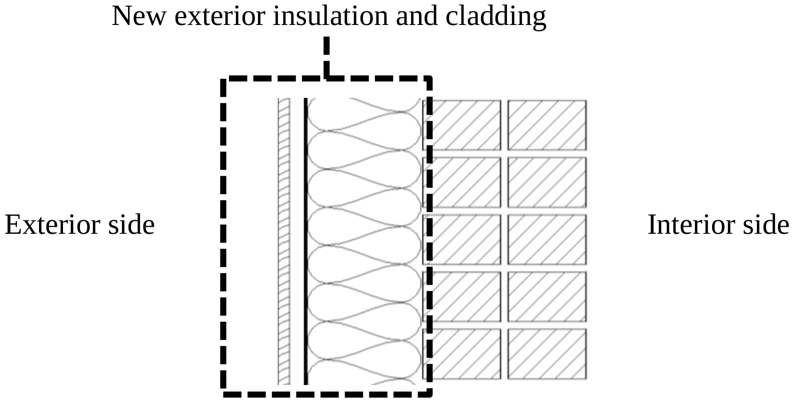


Figure 1: The exterior insulation method (Illustration by the author)

For the first method using the rigid foam insulation boards (such as EPS or XPS), the boards will be mechanically fixed or adhered directly onto the wall construction. A vapour retarder should normally be installed prior to the insulation layer. After the installation of the insulation layer, a three-step finish coating is applied, including a rendering sub layer applied on the exterior side of the rigid foam insulation, followed by a reinforcement mesh and a rendering finish layer. [48] [6] [49]

The second method using the light stud wall, can be constructed using wooden or steel studs. In the same way as with the first method, a vapour retarder should be installed prior to the light wall being fixed into place. The insulation material will then be placed in between the studs of the new light wall, followed by a wind board installed onto the studs, to protect the insulation material from wind exposure. After installation of the wind board onto the studs, a ventilated air gap should be constructed between the wind board and the cladding material, by fixing vertical battens onto the wind board. The air gap will serve to equalize the pressure, as well as to effectively remove any water which might have penetrated the cladding. [48] [6]

Using exterior insulation is generally seen as the most energy effective and moisture safe method of the three. As a result of placing the insulation on the exterior side, the temperature in the existing wall construction will become warmer and the dew point will be moved closer to the exterior surface. This is more favourable, from a moisture perspective, as it lowers the risk of interstitial condensation. In addition to more favourable moisture conditions, evidence also suggest, that insulating from the exterior side creates better possibilities to solve thermal bridges, as the entire building envelope will be covered by the insulation layer. [48] [6] Some sources claim that energy savings are up to 30% higher for exterior insulated buildings compared to interior insulated. Which primarily is due to the interior insulation method adding new thermal bridges to the existing building structure upon installation, which is not the case when the post-insulation is carried out from the exterior side. [6] [50] [51]

4.1.2 Cavity wall insulation

The cavity wall insulation method has long been considered easy and economic attractive, which is why the method is commonly used for energy retrofitting of buildings built between 1900 and 1970. Exterior walls from this period were commonly built of two brick layers with an air cavity in between. [52] To carry out the energy retrofit, a few bricks are removed or small holes are drilled in the exterior brick layer. After gaining access to the cavity space, the insulation material (e.g. mineral wool or granulate) will be blown in between the brick layers. [53] [54] [52] To ensure that the insulation will spread correctly e.g. under window and other openings, the insulation material will first be blown in from the lower part of the exterior wall and then later from the upper part [55]. After the cavity has been filled with the insulation material, the bricks are fixed back into place, and it is hardly even visible that the energy retrofit had taken place [53] [54] [52]. See Figure 2 below.

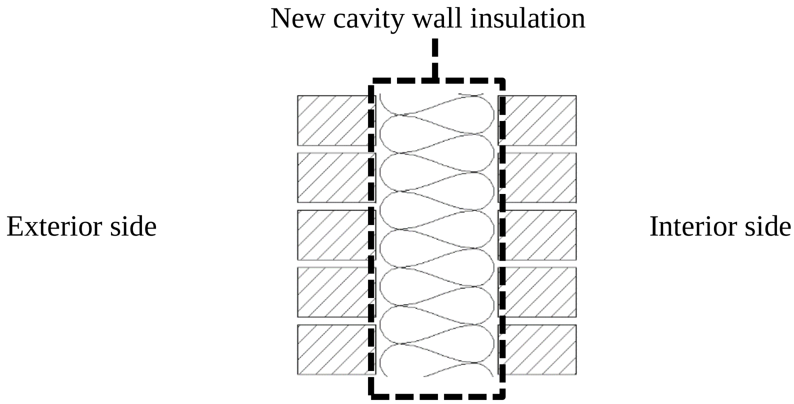


Figure 2: The cavity wall insulation method (Illustration by the author)

To avoid interstitial condensation from occurring, the existing interior brick layer should be airtight (maybe through the use of interior render), and not have cracks, holes or missing mortar joints. In addition to avoid interstitial condensation, moisture introduced due to wind-driven rain should also be considered, which requires the existing exterior brick layer to be in good condition. The brick layer should therefore be free of cracks, holes, freeze thaw damages or missing mortar joints. These problems should be fixed prior to the cavity space being filled with insulation material. Regarding the exterior finish, special care is recommended for rendered or painted surfaces, as a vapour tight finish can lead to moisture accumulation or freeze thaw damages in the wall. [54] [56] [6]

“Fixed” wall ties is considered as one the most important obstacle against using the cavity wall insulation method. A fixed wall tie can be described as a brick that have been placed across the cavity in the wall, to bind the two brick layers together. [56] [54] [52] These fixed wall ties have commonly been used for brick walls with a thickness around 360mm, and were often placed 50 cm apart within the wall. Thinner walls normally used thin metal ties. [54] If fixed wall ties have been used in the wall, they pose an increased risk that the insulation blow into the cavity space cannot be distributed correctly, as a result, leaving uninsulated air pockets. In addition to incorrect distribution of insulation, the fixed wall ties themselves also poses a problem. The fixed wall ties will create continuous thermal bridges through the walls, resulting in a lower effect by the energy retrofit. [56] [54] [52]

If all the measures are taken to ensure that the existing wall is in good condition prior to the insulation being blown into the cavity, the method should then be regarded as being relatively moisture safe [6].

4.1.3 Interior insulation

Regarding the interior insulation method, a new insulation layer will be installed on the interior side of the existing wall construction, traditionally through one of two construction methods. To lower the risk of mould growth between the existing wall and the new insulation, all organic residues are removed from the interior surface of the existing wall construction prior to the insulation work being commenced. See Figure 3 below.

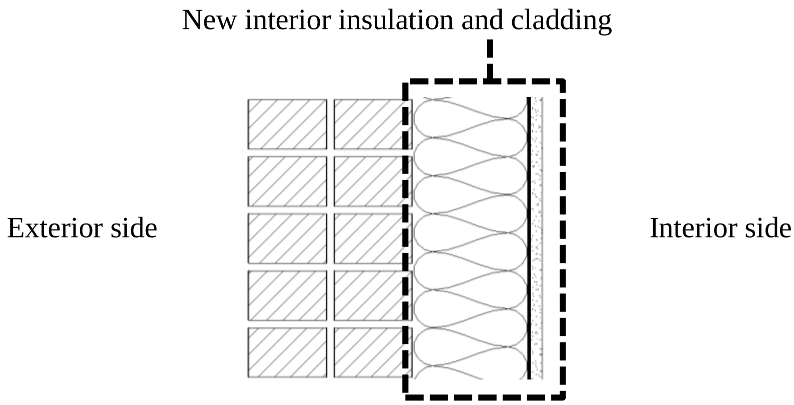


Figure 3: The interior insulation method (Illustration by the author)

The first method for installing the insulation require a light wall to be constructed on the interior side of the existing wall construction using wooden or steel studs. To avoid thermal bridges from the studs, the light wall should be placed a small distance from the existing wall construction (often 30-50mm). Keeping the light wall a small distance away from the existing wall also makes the erection of the wall easier, as the new light wall becomes fully independent of the imperfections of the existing wall. The first insulation layer should be placed in the cavity between the existing wall and the new light wall, followed by the second insulation layer, placed in between the studs of the light wall. After installing the insulation layers, the vapour retarder and interior cladding are then mounted on the interior side of the new light wall. [6] [57] [51] [54] [58] Regarding the choice of insulation material, most rigid insulation boards or flexible mineral wool batts can basically be used. If flexible insulation batts are used, an insulation thickness a bit larger than the cavity space is recommended. This will close air pockets between the existing wall and the new light wall, that is if the cavity is 50 mm then use 75 mm wool insulation. [51]

The second method for installing the insulation to the interior side of the existing wall uses rigid foam insulation boards such as EPS or XPS, which will be mechanically fixed or adhered directly onto the wall construction [59] [6] [57] [58] [60]. Mechanically fixing the boards onto the existing wall will create small but acceptable thermal bridges where the screws penetrate the insulation. To assure proper fixing, the interior surface must be even and in good condition, which means there should be no cracks, holes, dents or condensation problems. [6] The rigid insulation boards often come prefabricated with one or two layers of gypsum boards adhered onto the interior side of the board, with a special adhesive that will work as the vapour retarder. Prefabricated “insulation studs” are often used together with the insulation boards, to avoid thermal bridges in the connection points where the boards meet, and the junctions between the insulation boards are sealed with mastic sealants and tape to ensure airtightness. [6] [57] [58] [60]

4.1.3.1 Culturally heritage protection

Interior retrofitting of existing exterior walls, is primarily chosen where the more effective and safe exterior insulation method is not permitted, due to legislations or culturally heritage protection. As it was the case for the two school building at Lund University. In the case of a culturally heritage protected building, performing any major alterations to the exterior walls, roof construction or even interior surfaces (e.g. in the case of church paintings) may often not be permitted, if the alterations involve a risk, that the aesthetics values of the building could be compromised. These protections of the aesthetics values are often limited to exterior alterations, although depending on the protection level of the building, some interior alterations may not be permitted either. [61] [62] In the same way as with the culturally heritage protection, legislations related to building lines or plot borders often poses problems for the use of exterior insulation. Granted that the thickness of the exterior walls will increase towards the exterior, as a result the wall will exceed these borders, resulting in a refusal towards using the exterior insulation method. [61] [62] [5] [50]

In Sweden the cultural heritage protection mark known as “Kulturmärkning” or “K-märkning” (K-mark) is used. The municipalities can point out certain buildings or even whole neighbourhoods of high cultural value, as a part of the Swedish building preservation program. The K-mark itself do not have any formal or legal meaning to it, the designation merely describes that a building could be covered by a number of heritage protection restrictions. If a building receives the K-mark, it does not mean that the building automatically get any sort of legal restrictions placed upon it. [63] [64] [65] The local municipality or in some cases the County Administrative Board (Länsstyrelsen), are authorities who can place these restrictions on a K-marked building, if deemed necessary [63] [64]. The purpose of the K-mark is to work like guidelines, to help with the planning process in case of a building retrofit. Although the municipality do carry out continuous follow up on the work being performed on the K-marked buildings, to ensure the restrictions are followed. [63]

In certain cases, the municipality can go a step further and place legal restrictions on the K-marked building, the so called “q”, “k” and “Q” restrictions. The q restriction specifies in detail what parts of the building may or may not be modified, removed or if it should be maintained in a certain way. The k restriction specifies if certain precautions are needed during maintenance work to preserve specific traits on the building. [63] [64] [65] Lastly there is the Q restriction which is considered to be lighter in comparison to q- and k restrictions. The Q restriction only specifies how a building should be used in order to maintain its cultural value. But the Q restriction does not carry specific restriction against demolition of the building or what sort of activities may or may not take place within the building such as office area, shop space or apartments. [63]

4.1.3.2 The hygrothermal behaviour

In contrast to the exterior insulation method, where the existing wall construction becomes warmer and the dew point is moved towards the exterior surface, the interior insulation method will result in the existing wall construction becoming colder and the dew point will move towards the interior surface. Evidence show, that moving the dew point towards the interior surface, will increase the risk of interstitial condensation occurring. As a result of the increased risk for interstitial condensation, the risk of mould growth and/or freeze thaw damages occurring will also increase. In addition to the increased risk for interstitial condensation, the interior insulation method will also reduce the drying out potential of the existing wall construction, as the insulation will block the interior heat streams from leaking through the wall. As a result of the wall not being able to dry out as quickly as before the interior insulation was installed, will affect the moisture accumulation within the wall, leading to an increase in the moisture content. In case of high levels of wind-driven rain, walls with a reduced drying out potential poses an especially high risk for moisture related problems. [61] [5] [59] [6]

The thickness of the interior insulation is by Isover and SBi claimed to be of importance in relation to the drying potential of the wall. With greater insulation thickness, the risk of interstitial condensation will increase, as the drying speed becomes lower with the increased insulation effect by the thicker insulation layer. These sources recommend not using an insulation thickness greater than around 100mm (of traditional stone or glass wool). [51] [6] Although no other sources could be found, which would confirm the statement from Isover and SBi, most sources did use an insulation thickness ranging from 50 mm to 150 mm within their own experiments or recommendations. It should be mentioned that many sources did refer to the low interior insulation thickness with regards to the loss of interior floor space, as the loss of interior floor space increases with increasing insulation thickness. [62] [5] [61] [66] [54]

Further evidence was provided by Vereecken et al. (2015), who studied the energy saving capability of interior insulation assemblies while trying to avoid hygrothermal failure, using both vapour tight and capillary active insulation solutions. Their study was carried out using three insulation thicknesses for each of the interior insulation assembly: 20, 140 and 300mm. They found that when using a vapour tight interior insulation solutions, the thickness of the insulation affected the number of freeze thaw cycles occurring within the existing wall construction. As the insulation thickness increased, so did the number of freeze thaw cycles. It should be noted that their experiment did not include the application of an exterior surface coatings against wind-driven rain, and the number of freeze thaw cycles could possibly have been lowered by applying such coatings to the exterior surfaces. Although they did not explicitly recommend an insulation thickness no greater than 100mm, as most of the other sources did, her results did point in that direction and support the claim that the interior insulation thickness do matter for the moisture safety of the exterior wall construction. [40]

4.1.3.3 Airtightness

Airtightness is considered as the most critical of the problems regarding the use of interior wall insulation [6]. Assuring proper airtightness when using interior insulation can be a very difficult task, and it becomes harder, the longer the building has been in use [62]. Although difficult to accomplice, the airtightness of the interior insulation assembly, is a very important factor for both the moisture- and thermal performance of the building. The improved airtightness will in many cases show a greater impact on lowering the heating demand, than the insulation layer itself. [59] In addition to a decrease in the heating demand, there will also be a decreased risk of warm moist room air leaking through the construction, which would otherwise condensate upon contact with the interior surface of the existing wall, also known as interstitial condensation.

Vapour retarders, typically a type of plastic sheeting, are traditionally installed to achieve proper airtightness. In colder climates the vapour retarders are normally placed on the interior side, between the insulation and the interior cladding. As for all other construction solutions using vapour retarders placed near the interior surface, the vapour retarder is very exposed to mechanical damages such as penetration from nails and hooks for putter up items on the interior surfaces. Penetration of the vapour retarder should be avoided as far as possible; as large quantities of heat easily can escape through these small holes in the vapour retarder. [62] As a mean to avoid mechanical damages to the vapour retarder, many recommendations suggest that the interior insulation solution should be constructed in two parts. One part containing 2/3 of the insulation material, placed on the exterior side of the vapour retarder, and the second part containing the last 1/3, placed on the interior side, preferably 45mm or more of insulation on the interior side. [54] In addition to these recommendations, it should be noted that the vapour retarder should not be placed more than the 1/3 into the insulation material measured from the interior side, to avoid interstitial condensation from occurring. The vapour retarder should be constructed as tight as possible both in the junctions between construction parts, as well as where the vapour retarder overlap. [6] [50] [51] [54] The before mentioned placement of the vapour retarder maximum 1/3 into the insulation layer measured from the interior side is according to the Danish recommendations. The exact placement of the vapour retarder according to the Swedish recommendations on the other hand is a bit conflicting. SP Technical Research Institute of Sweden (SP Sveriges Tekniska Forskningsinstitut) also recommends the placement to be maximum 1/3 into the insulation layer [67]. However, according to the well-established moisture handbook (Fukthandbok) by Elmarsson and Nevander the placement should be maximum 1/4 into the insulation layer [68].

4.1.3.4 Wind-driven rain and water repellent coatings

Wind-driven rain is also considered as a critical moisture problem, which can cause a number of problems within the exterior wall construction hereunder surface soiling, algae growth, salt damage, frost damage, and mould growth [69] [70]. For old or historical buildings, wind-driven rain is often a big problem, as older exterior walls were constructed without proper insulation, ventilated cavity space or the use of a vapour retarder (often just constructed as solid masonry walls). As a result, there would be an increased interaction between the exterior and interior climate conditions with respect to the heat and moisture transfer. [71]

Wind-driven rain occurs when rain is given a horizontal velocity component by the wind, as a result the rain is deflected, making it possible for the rain to strike vertical surface such as exterior walls. The amount of wind-driven rain striking a vertical surface is determined by a number of factors, hereunder wind speed, building placement and shape, topography, orientation, tilt, and size of the rain droplets. [6] [71] Several studies have shown that the highest impact from wind-driven rain striking exterior wall surfaces occur near the corners and the top edge of the building, then the side edges, while the lowest impact occur in the central part of the wall surface. This phenomenon occurs due to higher wind speeds around the corners and edges of the building. [6] [71] [69] As a result of the rain strikes the exterior wall, a film will be formed on top of the surface, and the uptake of the surface material is then determined by the water absorption coefficient of the surface material. More porous materials such as masonry bricks and concrete can absorb large quantities of the rain striking its surface. [72] [6] Studies have shown that up to 70% of the rain water striking the surface of an exterior wall can be absorbed through capillary suction [62], and that the wind-driven rain can penetrate as deep as 200mm into the wall construction [72]. As the wind-driven rain penetrates deep into the exterior wall construction, the thermal transmittance will rise as the wall become wetter and wetter, as a result, causing a reduction of the already low insulating effect from the exterior wall. A reduced insulating effect will result in an increase in the thermal losses of the building, as well as an increase in the interior relative humidity as condensation more frequently will occur on the interior surface of the wall. [72] [5] [71]

Regarding the issue of wind-driven rain on exterior surfaces when the wall is interior insulation, evidence show that interior insulation installed on an exterior wall exposed to wind-driven rain, is likely to increase the risk of moisture related problems. As the wall will take longer time to dry out after the moisture has been introduced from the exterior side, due to the new insulation layer blocking the interior heat streams, as mentioned earlier. As a result of the large quantities of moisture introduced from and a reduce drying out process, a moisture accumulation will occur behind the vapour retarder inside the new light wall. [5] [62]

In contrast to the exterior insulation method, the interior insulation method does not provide any kind of protection for the exterior surface against the wind-driven rain. Other measures should therefore be considered in order to protect the exterior surface. Granted that the buildings are culturally heritage protected, there are two available relatively easy solutions which will not majorly alter the aesthetics of the building facades. The first solution is to apply a water repellent coating on the exterior surface, and the second solution is to construct a "fixed" rain protection.

The water repellent coating will fill the pores in the surface material, often to a depth of 10-20 mm (depending on coating type and porosity of the material), as a result, creating a water repellent layer blocking rain water from being absorbed through capillary suction. Water repellent coatings for exterior walls are often silicon based and can be almost completely colourless, possibly making the suitable for application on historical protected buildings. Although the water repellent coating is colourless, it might still change the appearance of the exterior surface as the wall might change in colour when drying up. [62] [72] [6] Water repellent coatings have been used on rendered facades for over 50 years in Germany. During this time, the water repellent coatings have shown promising results, which have eventually led to water repellent coatings becoming a part of the German Standards regarding surface applications for protection against wind-driven rain [72]. Studies of water repellent coatings applied on solid masonry walls have shown, that the coatings caused a decrease in the water content within the wall constructions to more acceptable levels, as the coatings protected the wall against moisture introduced by wind-driven rain [62] [73]. A water repellent coating for exterior surfaces can last more than 10 years [74] [75].

A number of issues should be taken into consideration when water repellent coatings are being considered. Presented below are three of the issues that the author deemed most relevant for this study. Firstly, the water repellent coating will only fill the small pores in the surface material, and it cannot fill larger cracks, holes, and gaps in the surface. These imperfections in the exterior surface need to be fixed prior to applying the water repellent coating. [62] [72] [6] If the imperfections are left unfixed, the result could be an increased risk of a concentrated moisture penetration occurring in these places. As the cracks, holes, and gaps will be exposed to the water, which would normally be absorbed higher up on the wall surface before the water repellent coating was applied, however this water will now run down and accumulate in these places. [6] Secondly, all sources which might introduce moisture to the wall construction should be fixed before the water repellent coating is applied, as the coating could great worsen the conditions of the wall, if these problems are left unfixed. In addition, if interior insulation is considered together with the water repellent coating, then the water repellent coating should be applied some time before any interior insulation work will be carried out. This will allow the wall to dry out as much as possible, as a result, there will be a reduced the risk of moisture becoming trapped inside the wall construction between the coating on the exterior surface and the vapour retarder on the interior surface. [73] [5] Thirdly, to avoid large quantities of moisture accumulating within the wall, Krus (1998) and Brandt et al. (2013) recommend that the water repellent coating allow for some vapour diffusion to occur. To assure that some amount of drying toward the exterior side will occur. Any small amounts of moisture which might have escaped from the interior side, should be allowed to pass right through the wall to the exterior side. [73] [50] Krus (1998) recommends that the water repellent coating should not increase the vapour resistance by more than 25%. As it is recommended that the construction allows for a small amount of drying to exterior side after the application of the water repellent coating. [73]

Regarding the “fixed” rain protection, in most cases the first step towards a moisture safe building is to design a constructive solution, deflecting or re-directing the water away from any sensitive areas such as joints or porous surface materials with high capillary capacity. This is the general idea by constructing a fixed rain protection, as recommended by the 4Ds approach. [76] If a fixed rain protection such as an overhang is used to protect the exterior wall against wind-driven rain, then it might not be necessary to apply any water repellent coating to the exterior surface. Fixed rain protection however only works for low rise buildings. As the fixed rain protection will only protect the first few meters of exterior walls located under e.g. an overhang. Protected against the wind-driven rain solely by the fixed protection, the exterior wall would be allowed to dry out from what little water that might strike it many times faster in comparison to applying a water repellent coating. To summarize, the fixed rain protection should be chosen over a water repellent coating for a desired fast drying process of the exterior wall. [73] Constructing a fixed rain protection such as an overhangs (or extending an existing overhang) will in many cases slightly alter the appearance of the building, as the roof construction will be altered. However, in the case where the culturally protection is placed exclusively on the exterior walls, it might then be considerably easier to apply dispensation for the roof construction than for the exterior walls.

4.2 Innovative retrofitting techniques

In recent years the building industry has been introduced to several innovative insulation products suitable for interior insulation work. Some products show increased thermal performance, and others claim to have solved the problem with interstitial condensation. The following chapters will introduce the innovative insulation products used in this study, including capillary active insulation, vacuum insulating panels, aerogel insulation, smart vapour retarders, and thermal insulating plaster.

4.2.1 Capillary active insulation

The properties of capillary active insulation allow the insulation to utilize its porous structure, to absorb any liquids that might occur due to interstitial condensation at the interface between the existing wall and the new interior insulation. Due to the pore size (0.1-1 μm) the capillary active insulation has a large liquid conductivity, which allows the insulation to redistribute the moisture back to the interior surface of the wall after it has been absorbed. At the interior surface, the liquids will slowly be released to the air inside the room. Besides having a construction resistant against interstitial condensation, the capillary active properties will also help to regulate the humidity in the occupied room. The insulation absorbs the indoor air moisture when the room is too moist and releases it back to the room when the indoor air becomes too dry. This helps to have a less variant indoor relative humidity. To ensure the capillary active function of the insulation, it is important that the interior cladding is vapour permeable. The insulation should therefore be installed without the use of a vapour retarder. Often is a type of capillary active plaster used and finished with a vapour open type of painting. [77] [78] [79]

Capillary active insulation is produced from a number of different materials hereunder calcium silicate, perlite, autoclaved aerated concrete, and wood fibres, all with different hygrothermal properties. Insulation panels made of *calcium silicate* have been used for more than 50 years, often for high temperature applications or as fireproofing insulation. [80] Calcium silicate insulation is made from a mix of Portland cement, fine silicate, cellulose fibres, and special filler materials [81]. For construction purposes the thermal conductivity is normally around 0.05-0.1 W/(m·K) [77] [80]. *Perlite insulation* is made from natural perlite, which is a type of volcanic glass containing high amounts of water [82] [83]. The perlite is heated up to around 1100 °C, making the volume expand up to 20 times the original, and as a result, creating the characteristic white granulate pebbles with good thermal properties [83]. The thermal conductivity is normally around 0.03-0.04 W/(m·K) for perlite insulation boards [83] [82]. *Autoclaved aerated concrete* is a type of highly insulating concrete. The autoclaved aerated concrete contains a mix natural materials hereunder lime, sand, cement, water and in some cases a small amount of aluminium powder. [84] [85] The highly insulating properties of the autoclaved aerated concrete is achieved by creating an air-filled porous structure within the material. As a result, the autoclaved aerated concrete is often 80-90% air, which also makes the autoclaved aerated concrete a relatively lightweight insulation material. The thermal conductivity of autoclaved aerated concrete is often around 0.04-0.1 W/(m·K). [86] [85] The *capillary active wood fibre insulations* use dry processed wood fibres as the main ingredient, and the production process is quite similar to that of wooden MDF boards. The wood fibre insulation comes both as flexible insulation batts and as rigid panels. The thermal conductivity is around 0.04-0.06 W/(m·K). [87] [88]

Several studies have in recent years addressed these capillary active insulation products, to assess their performance with respect to moisture and energy. Vereecken et al. (2014) studied the hygrothermal performance of several insulation materials applied onto a 300 mm solid masonry walls through hot box-cold box experiments. Where they evaluated ten insulation assemblies as well as an assembly with just the glue mortar which was used for a number of the other assemblies. Their study included both vapour open (no capillary active) and vapour closed assemblies, capillary active assemblies (CaSi, AAC and wood fibre), as well as traditional vapour closed assemblies applied with a smart vapour retarder. Each assembly was placed in the hot box-cold box, where the hot box was set to 35 °C with a relative humidity of 85%, and the cold box was set to 2 °C with a relative humidity of 45%. Wind-driven rain was not included in the experiment. To determine the hygrothermal performance of the assemblies, each assembly was x-rayed and weighed before, during and after the experiment. [61] The results from their experiment showed that the uninsulated wall and the vapour open assemblies experienced the highest increase in moisture content, while a smaller increase in the moisture content was noticed for the capillary active assemblies. The vapour closed assemblies and the smart vapour retarder assemblies showed very little increase during the experiment. Further assessments showed that the AAC assembly without the glue mortar experienced considerably lower increase in moisture content compared to the other capillary active assemblies as well as the AAC assembly with the glue mortar. In the end of their experiment they concluded, that although the capillary active assemblies did experience a higher increase in the moisture content compared to the vapour tight assemblies, the capillary active insulation did in fact reduce the risk of interstitial condensation. As the moisture got captured within the glue mortar and the insulation material, and redistributed inwards. Despite the reduced risk of interstitial condensation, Vereecken recommended to use the vapour tight assemblies for interior insulation work, as these assemblies proved superior with respect to avoiding interstitial condensation. [61]

In another recent case study, Bjarløv et al. (2015) studied the hygrothermal performance of three capillary active insulation materials, AAC, CaSi and IQ-Therm, through numerical simulations carried out in WUFI Pro. Their study also included the application of a water repellent coating on the exterior surface. Each of the insulation assemblies were applied onto the interior side of a 228 mm solid masonry wall with interior lime mortar render. The water repellent coating was applied in WUFI by reducing the adhering fraction of rain from the default 70% to 1%. Their simulation results showed that all the uncoated assemblies would experience excessive relative humidity levels at the interface between the masonry and insulation layer. While all the coated assemblies showed promising results, with very limited risk of mould growth, with the exception of the AAC assembly. In the same way as in the experiment by Vereecken et al. [61], regarding the AAC assembly with the glue mortar, their simulations also showed a large increase in the moisture content for the AAC assembly with the glue mortar. While the water repellent coating showed to be greatly beneficial for the interior insulated assemblies, their simulations also showed that applied onto the uninsulated masonry wall would increase the thermal resistance of the masonry wall, as the thermal resistance increases when the wall started to dry up. From their study, they concluded that capillary active solutions could prove beneficial for interior use, however, should not be recommended for use in areas with high levels of wind-driving rain, unless the wall can be protected by coating or a fixed protection. [62] In another Vereecken et al. (2015) studies, however, suggests that if the wall is protected from wind-driven rain by a water repellent coating or a fixed protection such as an overhang, then there would be no need for the capillary active insulation materials. As they claimed that the vapour tight solutions provide better protection against interstitial condensation, as well as better thermal performance, due to the lower λ-value of regular insulation such as mineral wool or EPS. [40]

4.2.2 Vacuum insulating panels

Vacuum insulating panel (VIP) is a highly insulating material which have primarily been used for insulating refrigerators, freezers and cold shipping boxes, due to the thin material thickness [89] [90]. The first type of vacuum insulation panels appeared already in the 1930's in Germany, but was introduced in the building industry as late as in the early 1990's [90]. The insulation panel consists of a core material often made of fumed silica, glass fibres, polystyrene or polyurethane, which has been wrapped in thin metalized multi-layered polymer foil creating an airtight layer around the core material [90] [89] [91]. The core of the panel is then evacuated, as the removing the majority of the gas molecules will greatly lower the heat transfers through convection and conduction. As a result of removing most of the gas molecules, the thermal conductivity of the panel will be greatly lowered. [90] [89] The thermal conductivity of vacuum insulation panels is often around 0.005-0.006 W/(m·K). Although the metalized multi-layered polymer foil wrapped around the panel is almost fully airtight, the panel will over time, lose part of its insulating effect, as a result of air and moisture diffusion through the foil. Evidence from field experiments using vacuum insulating panels suggest, that a thermal conductivity of around 0.007-0.008 W/(m·K) can be used as the so called "aged design value" for the vacuum insulation panels. The aged design value is the thermal conductivity of the panel after 25 years of use. [91] [90] Furthermore, it should be noted that the vacuum insulation panels come in certain shape and sizes, and cannot be altered on the building site. The panels are very fragile, and if punctured the thermal conductivity will increase by around 500%. [90]

In Sweden, Johansson (2014) studied the performance of vacuum insulating panels through one-dimensional and two-dimensional hygrothermal simulations, as well as through large-scale laboratory testing. The target of his study was to investigate the hygrothermal performance of the vacuum insulating panels applied on the interior side of a solid 1½ brick wall or 380 mm solid masonry wall, with an interior plaster layer. And for that purpose four types of bricks and dix types of mortars were investigated in connection with a 20 mm vacuum insulating panel. The results of his study showed that the energy use could be reduced considerably by applying even thin thicknesses of the vacuum insulating panels. In contrast to the energy reducing potential, the hygrothermal results showed an increased risk for freeze thaw damage as well as a large increase for the relative humidity in the wall, as the drying potential was reduced due to the interior insulation. [92]

4.2.3 Aerogel insulation

Aerogel is a high performance insulation type, where the insulating effect comes from encasing air molecules within a nano-porous foam material made from fibre reinforced silica aerogel. Aerogel insulations do not use any special type of gas or vacuum, and will therefore not loose efficiency over time. The thermal conductivity of aerogel insulation is often around 0.014-0.015 W/(m·K). The aerogel insulation is relatively robust and performance lifespan of over than 50 years. The insulation often come as thin blankets (10-20mm) that are easy to work with, as it can be cut with normal scissors or hobby knives as well as be mechanically fixed to the existing wall by screws or nails. [93] [94] In a case study Galliano et al. (2015) studied the hygrothermal behaviour of three innovative prototype insulation materials for interior retrofitting, including a rigid silica aerogel panel and a flexible silica aerogel insulation batt with a fabric finishing layer. Their study included a number of laboratory testing such as thermal conductivity measurements at dry and wet conditions, vapour permeability testing as well as water absorption testing. Based on the laboratory results they concluded that the silica aerogel prototypes would be suitable for interior retrofitting. [95]

4.2.4 Smart vapour retarders

The function of a normal vapour retarder is to keep the warm moist indoor air from escaping the room, to avoid interstitial condensation, while the smart vapour retarder (made from nylon-based materials) is designed to change its vapour permeability depending on the relative humidity in the room during the year. The retarder will during the dry winter months where the relative humidity outdoor is low, have a low vapour permeability, as a result, being tight against vapour diffusion and work like normal vapour retarder. While during the humid summer months where the relative humidity outdoor is high, the retarder will have a high vapour permeability, making the retarder swell up and develop a porous structure allowing for vapour diffusion through the retarder to occur. When the humid summer months are over, and the relative humidity outdoor start to become too dry, the retarder will close up and become tight again. [96] [97] The smart vapour retarders will like the normal vapour retarders be installed on the warm side of the insulation material [96]. The ability of the smart vapour retarder, to change its vapour permeability allow for an effective way of drying out the construction towards the interior surface during the hot summer months, as a result, assure a construction free from interstitial condensation [96]. It should however be noted that a good ventilation flow might be necessary during the summer period to ensure that the moisture released from the construction will be taken out of the building. The smart vapour retarder is suitable for cold climates, or climates which experience big changes between summer and winter. However, the retarder is not suitable for hot climates with long periods of high relative humidity, or buildings with constant high relative humidity such as indoor swimming pools or spas. As the constant high relative humidity will keep the retarder open for diffusion. [97]

Künzel (1999) studied the hygrothermal performance of a cathedral roof installed with a smart vapour retarder. The field study was carried out for a cathedral roof consisting of wooden beams with insulation, and zinc cladding. The roof had a 50° inclination, facing North and South. On the interior side roof was divided into three section, one with regular vapour retarder of polyethylene film, one with Kraft paper, and the last with a smart vapour retarder. From his study Künzel concluded that the smart vapour retarder effectively lowered the risk of moisture related problems, as the retarder allowed the roof construction to dry out during the warm period of the year. [98] Vereecken also documented promising results from her case studies involving smart vapour retarders applied in connection with interior retrofit assemblies [61] [40].

4.2.5 Thermal insulating plasters

A few of the before mentioned insulation types are also available as insulating plasters, hereunder a lime-based aerogel insulating plaster with a thermal conductivity around 0.028 W/(m·K) as well as a cement-based perlite insulating plaster with a thermal conductivity around 0.055 W/(m·K). The insulating plaster often works as vapour tight solutions, and will therefore not have capillary active properties, to redistribute moisture within the wall construction. The insulating plasters often need a base coating to be applied to the existing wall a few days in advance, for the plaster to be able to stick to the wall. Upon application, a single layer insulating plaster can be applied in thicknesses around 50-80mm. If thicker layers are needed, a 24 hours hardening period is required before the second layer can be applied. [99] [100] In a case study Ibrahim et al. (2014) studies the hygrothermal performance of applying aerogel-based insulating rendering to exterior wall. Their study was carried out through numerical simulations in WUFI, where the aerogel render was applied on the interior- and exterior side as well as on both sides of a solid concrete wall. In addition to the aerogel rendering, their study also included EPS assemblies set up in the same manner. From their study, they concluded that aerogel-based insulating rendering would not be suitable for interior retrofitting as the results showed an increasing trend for the total water content without the chance to dry out. The results showed a risk of interstitial condensation for 40-50% of the time period which was studied. In addition to studying the application on the different sides of the exterior wall, their study also tested the effect of altering the insulation thickness. From which they concluded that adding more thickness on the interior side would worsen the hygrothermal performance. [101]

5 Methodology

5.1 Overview

The study was based upon data provided by Akademiska Hus in Lund. Akademiska Hus is one of Sweden's largest real estate companies, with a market share of 60%. The company is governmental owned, and focuses exclusively on renting out building for educational purposes such as colleges and universities. [102] The data provided included architectural and engineering drawings for both the A- and V-building, calculated and measured data regarding energy use for the A-building, as well as a general descriptions of the construction parts. Located in the A-building is the Department of Architecture at Lund University, while the V-building hosts the educations for fire technology engineering, risk management, as well as civil engineering [103] [104]. The study was limited to analysing only the exterior wall and roof constructions, and was carried out in six phases, se Figure 4 below.

1. The existing constructions were assessed and relevant literature was reviewed, thus determining the extent of the existing knowledge in the field as well as to generate ideas for construction assemblies.

2. Project goals, simulation cases and the expected results were defined.

3. Wall and roof assemblies were developed based upon the literature review, and simulated in WUFI against current and future climate scenarios.

4. The thermal bridging effect of the approved assemblies were simulated in HEAT2.

5. The approved assemblies and thermal bridging results from HEAT2 were then implemented into the whole-building energy simulations (carried out in Design Builder, Honeybee, and IDA ICE), and simulated against current and future climate scenarios.

6. The feasibility of the approved assemblies was then studied with respect to LCA and LCC, taking into account the material usage for each of the assemblies and energy use from the energy simulations.

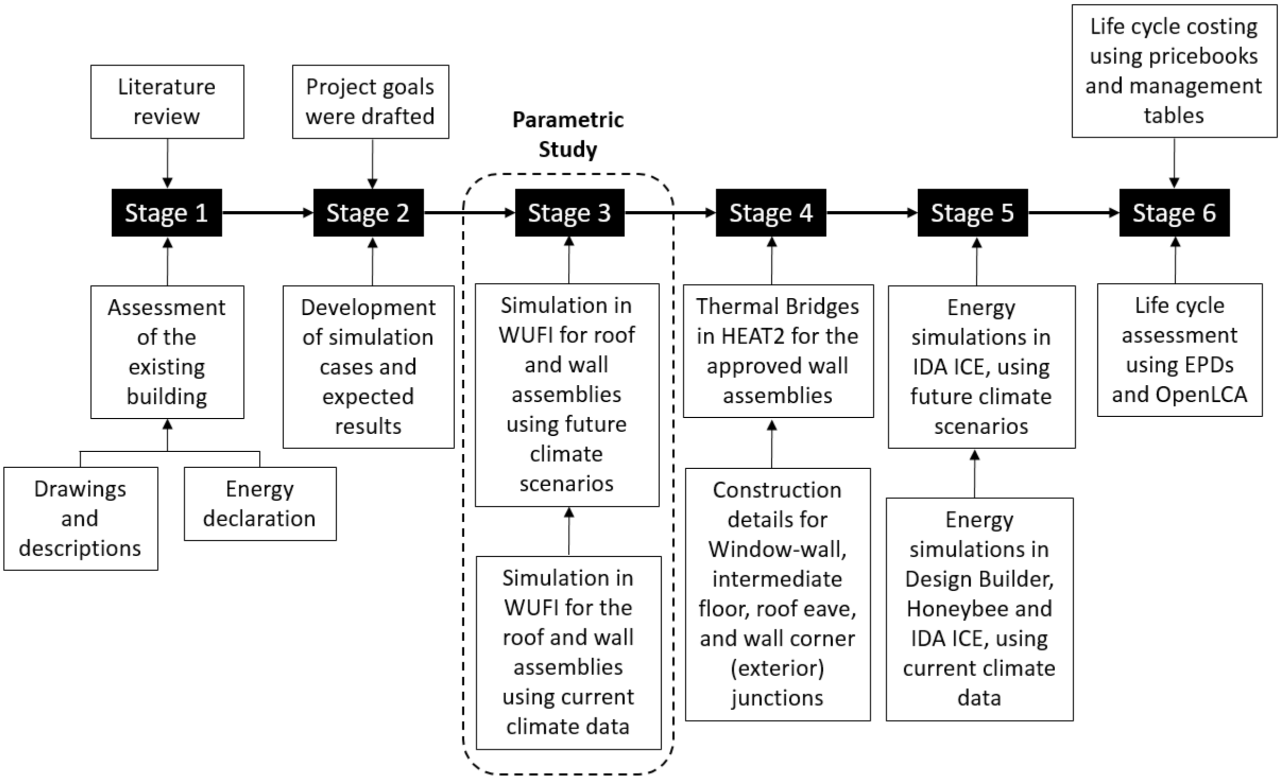


Figure 4: Project overview (Illustration by the author)

5.2 Software

The following part is an overview of the software used throughout the study:

- *Autodesk AutoCAD* is a 2D and 3D computer-aided-design and drafting software [105], the software was exclusively used for assessing the building plans, sections and details.

- *Sketchup* is a 3D modelling software with a wide range of drawing applications and an easy-to-use interface, allowing the users to build fast 3D models [106]. Sketchup was used as the main drawing tool for creating the building models.

- *Sketchup Plug-ins*

    - *Legacy OpenStudio* is an open source plug-in for Sketchup allowing the user to create and edit the building geometry of an EnergyPlus input file in the easy-to-use interface of Sketchup [107]. Furthermore, the Legacy OpenStudio plug-in allows for a number of export possibilities to simulation software such as OpenStudio, Design Builder and Honeybee. Legacy OpenStudio was used for creating the building models and exporting to the simulation software.

- *Design Builder* is an advanced simulation software built around the EnergyPlus simulation engine with an easy-to-use interface, allowing the users to model building heating, cooling, lighting, ventilation and other energy flows in detail [108]. Design Builder was used to calculate the thermal performance of the buildings.

- *IDA Indoor Climate and Energy* is a detailed and dynamic multi-zone simulation software, allowing the user to study the energy performance and thermal indoor climate of a building [109]. IDA Indoor Climate and Energy was used to calculate the energy performance of the buildings.

- *Rhino 5* is a free form surface modelling software using Non-Uniform Rational Basis Spline (NURBS), which are mathematical representations of 3D geometry [110]. There are a large number of plug-ins available for Rhino 5 which greatly expand the capabilities of the software, a few of these plug-ins were used. The imported Sketchup geometry was slightly altered in Rhino to make the 3D model ready for use in the Grasshopper plug-in.

- *Rhino 5 Plug-ins*

    - *Grasshopper* is a graphical algorithm editor which is integrated with the 3D modelling tools within Rhino [111]. Grasshopper was used as the main working interface while working with Ladybug and Honeybee, and a number of the native components from Grasshopper were used in the creation of the script for the energy simulations.

    - *Ladybug* is an open source environmental plug-in for Grasshopper, used to help architects and engineers to create environmental-conscious building designs. The plug-in allows the user to import climate date and provides a series of decisionmaking tools. [112] Ladybug was mainly used for importing climate date, analysing simulation results.

- *Honeybee* is another open source environmental plug-in for Grasshopper. Honeybee connects Grasshopper to series of validated simulation engines such as EnergyPlus, Radiance, Daysim, and OpenStudio, allowing the user to perform building energy- and daylighting simulations through the graphical algorithm editor in Grasshopper. [112] Honeybee was used to calculate the thermal performance of the buildings.

- IDF-Editor is an optional software installed along with EnergyPlus, it allows the user to create or edit the EnergyPlus input data files (IDF) in a simple spreadsheet interface [113]. The IDF-Editor is a very useful tool to assess the IDF file which is generated when carrying out an energy simulation in a simulation software using the EnergyPlus engine. The IDF-Editor was used to assess and compare the input date used in Design Builder and Honeybee, to ensure comparable simulation results from both software.

- *WUFI Pro* is dynamic hygrothermal analysis software for evaluating the moisture conditions in the building envelope by performing one-dimensional hygrothermal calculations through a cross-section of the building component. The software account for a number of factors such as built-in moisture, driving rain and capillary transport. [114] WUFI was used to assess the exterior walls and roof constructions.

- *HEAT2* is a simulation software for two-dimensional heat transfers performed either as steady-state or transient calculation, allowing the user to analyse the thermal bridges in the building envelope [115].

- *Autodesk Revit* is a building information modelling software, allowing the users to design detailed 3D building models as well as annotate the models as 2D drafting [116]. Revit was primarily used for drawing the construction details.

- *OpenLCA* is an open source Life Cycle Assessment and footprint software with a large material database. The software allows the user to perform professional Life Cycle Assessment and footprint calculations. [117] OpenLCA was used to assess the environmental impact of the different construction solutions.

- V&S Prisdata is pricing databased used within the Danish building industry containing material prices, labour prices, social expenses as well as prices for rent of equipment and machinery [118]. The V&S Prisdata was used for the Life Cycle Cost.

- *Microsoft Excel* was used to manage both the input data for the different simulation software as well as for assessment of the simulation results, LCA and LCC calculations.

5.3 Case buildings

The case buildings in this study was the School of Architecture (A-building), and the building for civil engineering (V-building), both at the Faculty of Engineering at Lund University in southern Sweden, see Figure 5 and Figure 6 below.

Figure 5: A-building (Photo by the author)

Figure 6: V-building (Photo by the author)

5.3.1 Historical background

The A- and V-building along with many other public buildings in the city of Lund were designed by the Swedish architect and artist Klas Anshelm. Anshelm was born 14th of February 1914 and he grew up in Svegatan in Gothenburg. Already as a kid he showed a talent for model building and drawing, and in 1936 Anshelm began his architect education at Chalmers University of Technology, from which he graduated in December 1940. During his education Anshelm received high marks in architectural history, technical- and freehand drawing. [119]

The first years after his graduation Anshelm worked for Hans Westman in Lund, and during this time he was called in for military service multiple times as skier and signaller. In 1944 Anshelm was accepted for a position at Wejke & Ödeens Architect office in Stockholm, he worked for Wejke & Ödeens in Stockholm for the next three years. During this time Anshelm got involved in the general planning of Lund University. Then in 1947 Anshelm was offered to take over the work on the general planning, on the condition that he would establish his office in Lund. Anshelm accepted the offer and moved to Lund with his wife and son. [119]

In the end of the 1950's the Swedish government was planning to build its third technical university, in an attempt to heighten the education level in the country. Through statistical investigation it was decided that the Lund/ Malmo area would attract more engineering students in comparison to Umeå and Uppsala. In connection with the new technical university in Lund, Anshelm was chosen as project architect. Anshelm was chosen as he had already been involved in the general planning of the university during most of the 1940's, as well as through recommendation by the Swedish Construction Authorities who had experience with Anshelm from the construction of the university building "Midicinarberget" in Gothenburg.

The design of the technical university in Lund was the biggest project of Anshelms career, and during the 1960's Anshelm designed a total of six large university buildings. [119]

Anshelms initial idea for the university buildings was that they would be built in a semi-circle around two small lakes, and the buildings would be connected by corridors. Later this design was reshaped into 6 detached buildings, of which most would be placed in a straight line going north to south, when Anshelm got inspired by Århus University in Denmark designed by Fisker, Möller and Stegman. [119]

Before the planning process of the buildings for the technical university in Lund was completed, the mathematics building (F-building) was erected. The mathematics building would serve as a prototype building for the rest of the technical university. The School of Architecture was the next building to be erected, followed by the building for civil engineering, Electronics technology and Machine technology, and lastly the building for Chemistry. Most of the university buildings were constructed following the same base principles hereunder module line, heights and dimensions, but also the use of materials and construction solutions are quite similar. [119]

The layout of the buildings was also designed upon the same base principles. Anshelm designed the layout in such a way that the building would have a tall part placed in the middle (which Anshelm called the spine of the building), where offices would be located (orange hatching). One lower part on the western side where classrooms and auditoriums would be located (blue and red hatchings respectively), and finally one lower part on the eastern side where workshops, atelier and laboratories would be located (green hatching), see Figure 7. [119]

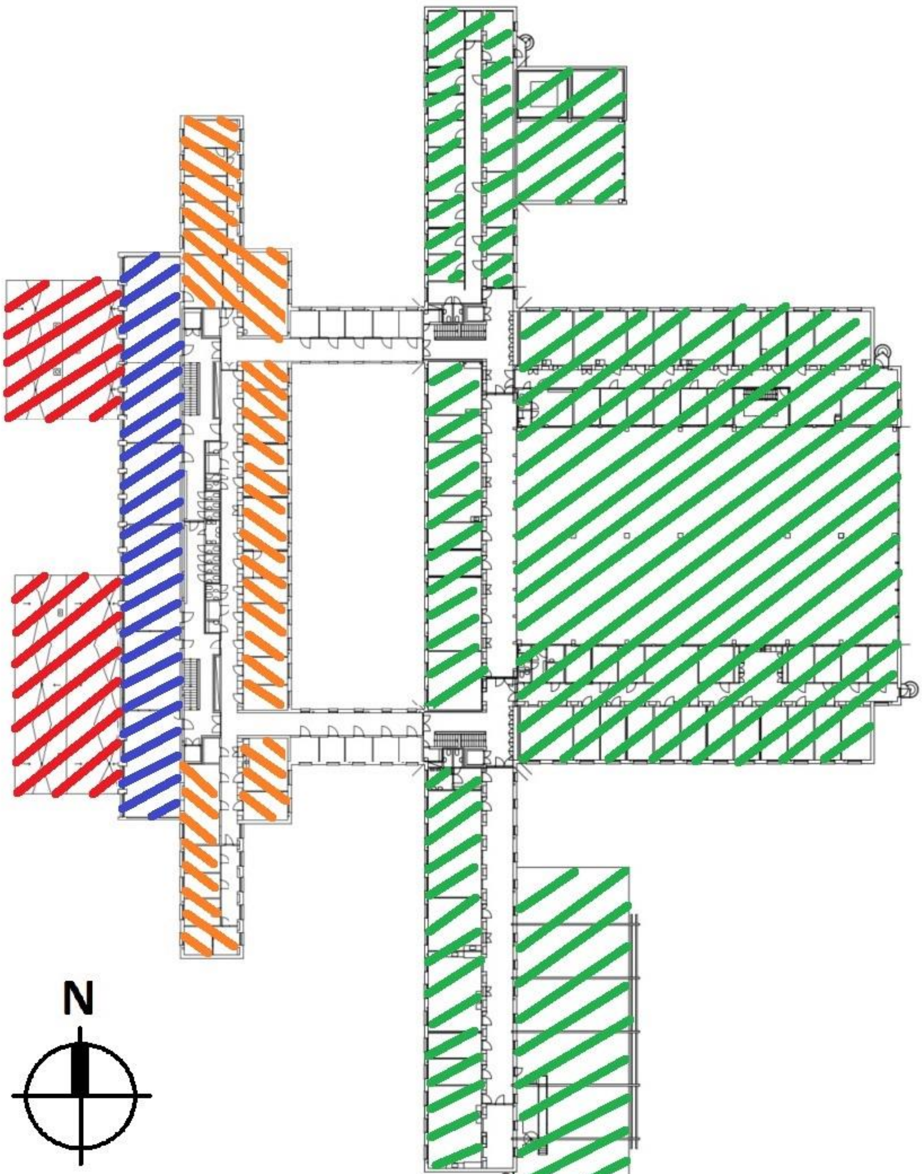


Figure 7: Floor plan showing the base principles of the layout (Illustration by the author)

After completing the project for the technical university in Lund, Anshelm continued working as an architect from his office in Lund until his death on the 6th of May 1980. During his career Klas Anshelm was considered to be a very productive architect, who constructed well over 100 buildings, and through his 33 years working in Lund his designs have greatly characterized the cityscape of Lund. [119]

5.4 Weather data

The purpose of this section is not to go deep into details on how climate models are being developed, but rather to briefly explain the characteristics of the climate models used to generate the climate date sets which are used in this study. For more information regarding the climate models [120] [121]. The climate data sets used in this study for the hygrothermal simulations were based on results from the two Global Climate Models IPSL (by the Institut Pierre Simon Laplace in Paris, France) and CNRM (by the National Centre for Meteorological Research in Météo, France), which both used the A1B emissions scenario. The Global Climate Models were dynamically downscaled using the Regional Climate Model RCA3 (by the Rossby Centre in Norrköping, Sweden). The RCA3 used a spatial resolution of 50 km by 50 km. For the purpose of this study, three 30-year periods were simulated for each of the two climate models. The three 30-year periods were 1961-1990, 2021-2050 and 2071-2100. In contrast to the two latter 30-year periods, the first 30-year period was simulated as a mean to compare the climate models to the current climate data set, as the climate file for the current climate data in WUFI is a Typical Meteorological Year (TMY) of the 1961-1990 period. A TMY consist of months selected from individual year which are linked together to form a complete year which represents the most probable climate conditions of the 30-year period in a one-year climate data set [122]. The 1961-1990 results should therefore be relatively comparable to the one-year climate which was used as the current climate data. The time period 1961-1990 will be referred to as the "reference period" throughout the report. The climate data was provided by the Department of Building and Environmental Engineering, Division of Building Physics at Lund University [123].

Climate date from Gothenburg were used for the hygrothermal simulations carried out in WUFI since 1) the weather conditions for Gothenburg is very similar to that of Lund, 2) the future climate data sets for Gothenburg has been previously created and verified for WUFI simulation [124], 3) the mould conditions has been previously investigated for some southern cities in Sweden and Gothenburg was shown to be the one posing the highest risk [120], and the retrofitting measures would therefore be assessed for conditions with the highest risk. The climate data sets used for the hygrothermal simulations are as follows:

Current climate data:
Göteborg.WBC (WUFI Binary Climate file)

Future climate scenarios:
RCA3_CNRM_A1B_50km_Gothenburg_1961_1990
RCA3_CNRM_A1B_50km_Gothenburg_2021_2050
RCA3_CNRM_A1B_50km_Gothenburg_2071_2100
RCA3_IPSL_A1B_50km_Gothenburg_1961_1990
RCA3_IPSL_A1B_50km_Gothenburg_2021_2050
RCA3_IPSL_A1B_50km_Gothenburg_2071_2100

In contrast to the hygrothermal simulations using climate data from Gothenburg, the energy simulations used climate data from Malmo/Lund. Two climate data sets were used for the current climate simulations due to compatibility issues between the simulation software. The Lund climate data were used for the current simulations in Design Builder and Honeybee, while climate data from Malmo were used in IDA ICE. In comparison to Malmo, the city of Lund is located approximately 20 km North-East and a bit more inland, however, it was assumed that difference in the location would have a marginal impact on the simulation results and would therefore be neglect able. In contrast to the current climate simulation, the future climate simulations were carried out using future climate data for Lund only. Due to the before mentioned compatibility issues as well as simulation simplicity, the future climate simulations were carried out only in IDA ICE.

As seen for the hygrothermal simulations, the climate data sets used for the energy simulations were also based on results from the two Global Climate Models IPSL (by the Institut Pierre Simon Laplace in Paris, France) and CNRM (by the National Centre for Meteorological Research in Météo, France), which both used the rcp85 greenhouse gas concentration trajectory. In addition to the rcp85 trajectory, the rcp45 greenhouse gas concentration trajectory was also used for the CNRM climate model. The Global Climate Models were dynamically downscaled using the Regional Climate Model RCA4 (by the Rossby Centre in Norrköping, Sweden) for the climate data used for the energy simulations. The RCA4 used a spatial resolution of 12.5 km by 12.5 km. In contrast to the hygrothermal simulations, TDY (typical downscaled year) [125] climate data sets for three time periods were used, instead of the 30-year climate data. The three TDY time periods were 2009-2038, 2039-2068, and 2069-2098. TDY climate data sets represents the typical climate conditions occurring within the three given time periods in one-year climate data sets. The TDY climate data sets were primarily used due to excessive simulation time with the 30-year climate data sets. The climate data was provided by the Department of Building and Environmental Engineering, Division of Building Physics at Lund University. For more information regarding the climate models [120] [121] [125]. The climate data sets used for the energy simulations are as follows:

Current climate data:
Lundhour.EPW
SWE_MALMO-STURUP_026360_IW2.PRN

Future climate scenarios:
SMHI_RCA4_CNRM_CERFACS_CNRM_CM5_rcp45_2009_2038_TDY
SMHI_RCA4_CNRM_CERFACS_CNRM_CM5_rcp45_2039_2068_TDY
SMHI_RCA4_CNRM_CERFACS_CNRM_CM5_rcp45_2069_2098_TDY
SMHI_RCA4_CNRM_CERFACS_CNRM_CM5_rcp85_2009_2038_TDY
SMHI_RCA4_CNRM_CERFACS_CNRM_CM5_rcp85_2039_2068_TDY
SMHI_RCA4_CNRM_CERFACS_CNRM_CM5_rcp85_2069_2098_TDY
SMHI_RCA4_IPSL_IPSL_CM5A_MR_rcp85_2009_2038_TDY
SMHI_RCA4_IPSL_IPSL_CM5A_MR_rcp85_2039_2068_TDY
SMHI_RCA4_IPSL_IPSL_CM5A_MR_rcp85_2069_2098_TDY

5.5 Hygrothermal simulations

The hygrothermal simulations were carried out using WUFI, and the process began by assessing the existing exterior wall- and roof-constructions using the data provide by Akademiska Hus. The existing buildings consisted of four different wall constructions as well as three different roof constructions. The solid brick masonry wall with interior plaster was the only wall construction used in the assessments, as this wall type was predominantly used in the two buildings as well as due to simulation simplicity. In contrast to the wall constructions, all three roof constructions were assessed, as all three roof constructions covered a large part of the total roof area. After assessing the existing constructions, a number of assemblies were developed for both the exterior walls (interior insulation only) as well as for the roof. Manufacturer recommendations and detail drawings were used for the design of the wall and roof assemblies, to assure correct material layers and placement. After assessing both the existing and the new assemblies with the current climate data, future climate date sets were used to assess each of the assembly passing the criteria for the current climate data. The climate data sets used for the hygrothermal performance was as mentioned in section 5.4.

5.5.1 General WUFI inputs for the exterior wall assemblies

In WUFI the climate data from Gothenburg would be analysed and the prevailing direction of driving rain was determined to be south, see Figure 8 below. It was necessary to determine the prevailing direction of driving rain. As the prevailing direction of driving rain and due north, would be the two most critical wall orientations to simulate within WUFI. [126] As for the indoor climate conditions, the default setting was used, which was specified according to EN 15026.

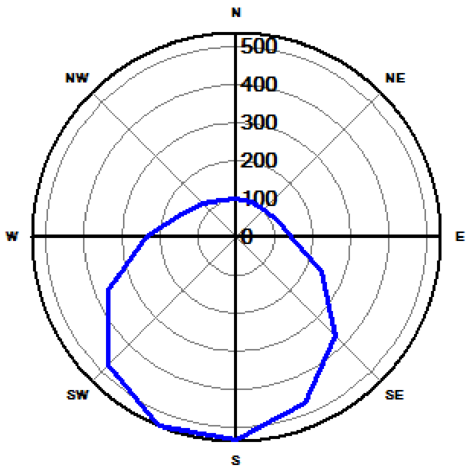


Figure 8: Prevailing direction of wind-driven rain for Gothenburg [127]

The building height was set to 10-20 m, to correspond to the actual building heights, and the wall inclination was keep as default, 90 °. As for the surface transfer coefficients, the exterior- and interior heat transfer resistance were set to 0.0588 $m^2 \cdot K/W$ and 0.125 $m^2 \cdot K/W$ respectively, which was default for a wall construction. The short-wave radiation absorptivity was set to 0.68, which was the predefined value for brick surfaces. The remaining coefficients were kept as default.

The initial moisture and temperature conditions within the wall construction were kept as default, which was relative humidity at 80 % and a temperature of 20 °C.

5.5.2 Calculation period

The calculation period within WUFI was set to 30 years, for more accurate comparison between the simulations using current and future climate data, as the future climate scenarios are required to be simulated for a period of 30 years. In addition to making the results easier to compare to the future climate scenarios, the calculation of zero-crossings should normally be carried out for long periods of time, as mentioned in section 3.4.2. A 30-year period was therefore chosen for calculating the number zero-crossings in the wall assemblies.

5.5.3 Exterior wall assemblies

The WUFI base case was created using an assembly consisting of a 395 mm thick solid brick masonry wall with 15 mm interior gypsum plaster. The base case was denoted with the model ID “A”, see Figure 9. Material specifications for all the assemblies are shown in Appendix A. Two monitor positions were considered, the first one located approximately 20 mm from the exterior surface of the wall, and the second monitor at the interface between the brick and the interior gypsum plaster. The purpose of the first monitor, near the exterior surface, was to measure the fluctuations in moisture content and temperature during the year, which would be used to determine the risk of frost damage due to freeze-thaw. While the purpose of the second monitor was to measure the fluctuations in temperature and relative humidity at the interface between the brick and the interior gypsum plaster, which would determine the risk of interstitial condensation within the construction. And as a result of determine the risk of interstitial condensation, possibly also determining the risk of mould growth. These monitor positions were also used for the modified cases, where the second monitor would determine the risk of interstitial condensation between the existing brick part and the interior insulation assembly. The monitor positions will be illustrated by two black dots as shown on Figure 9.

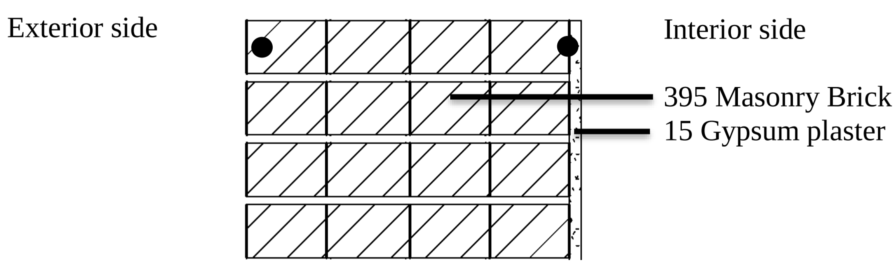


Figure 9: Wall Model A (Illustration by the author)

A total of 18 different interior insulation assemblies were chosen for this study, of which 10 had capillary active properties. Most if not all of the innovative insulation material used for the 18 wall assemblies were commercially available on the market at the time of the study. A short description for each assembly is found below, however for more information regarding the layers, thickness of layers, and thermal properties, see Appendix B.

The first assembly was a traditional insulated stud wall solution, using wood or steel studs with generic mineral wool in between the studs, build up in two layers as described in section 4.1.3. A vapour retarder and gypsum plasterboard was placed on the interior side of the stud wall to ensure airtightness. This setup was denoted with the model ID "B".

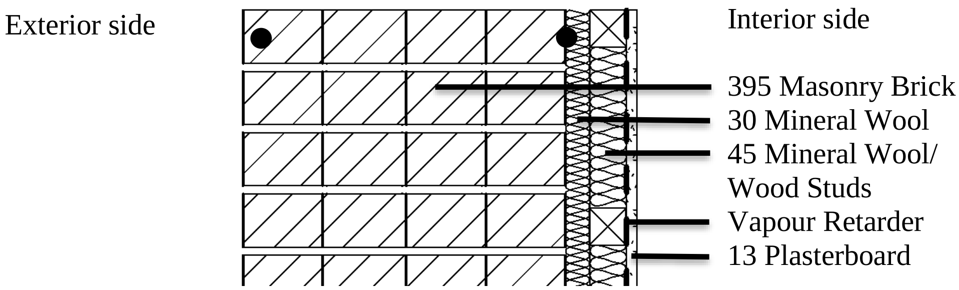


Figure 10: Wall Model B (Illustration by the author)

The second assembly was a traditional EPS solution where the rigid boards were mechanically fixed or adhered to the existing wall, and the vapour retarder and gypsum plasterboard was placed on the interior side, as describes in section 4.1.3. This setup was denoted with the model ID "C".

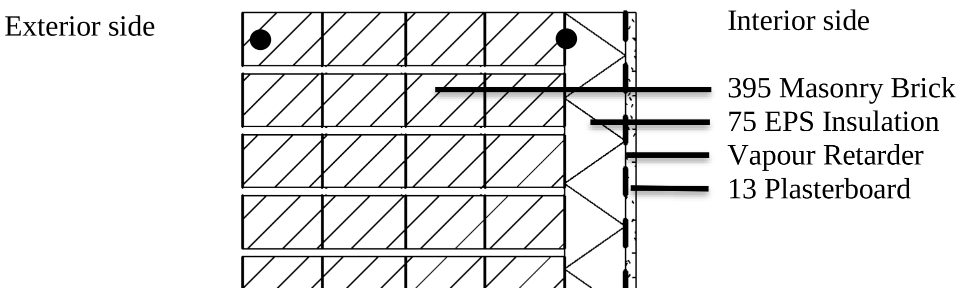


Figure 11: Wall Model C (Illustration by the author)

The third assembly was a setup using a generic vacuum insulating panel from the WUFI database together with a thin EPS board for protection, as well as a vapour retarder and gypsum plasterboard was placed on the interior side [128]. This setup was denoted with the model ID "D".

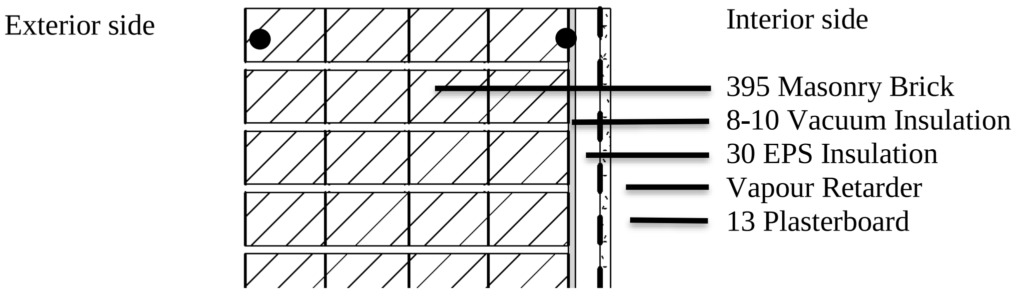


Figure 12: Wall Model D and E (Illustration by the author)

The fourth assembly was a vacuum insulating panel setup similar to model D, as seen in Figure 12. However, instead of the generic panel, the vacuum insulating panel Isover Vacupad was used. The material properties of the Isover Vacupad panel differ slightly from the generic panel. This setup was denoted with the model ID "E".

Assemblies five to eight were all capillary active solutions using different types of generic calcium silicate boards from the WUFI data base (Calcium silicate AI, Calcium silicate Lüneburg, Calcium silicate Washington, and Calcium silicate Masea), all with slightly different properties. The assemblies consisted of first a layer of cement lime plaster, which was applied directly onto the existing wall, next a type of capillary active adhesive, then the calcium silicate board and lastly a type of capillary active top plaster. [77] These setups were denoted with the model ID "F", "G", "H" and "I".

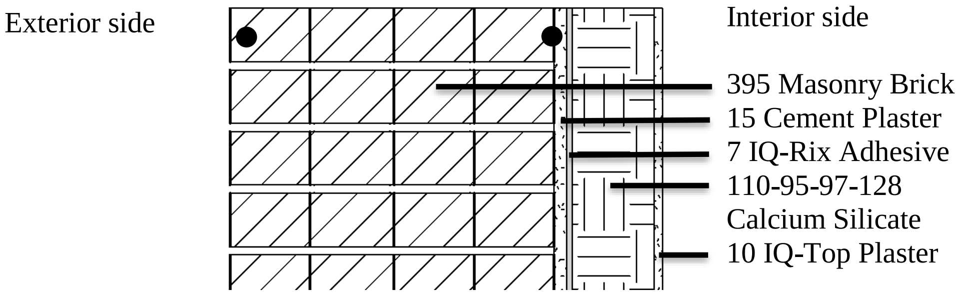


Figure 13: Wall Model F, G, H and I (Illustration by the author)

The ninth assembly was a type of capillary active solution named IQ-Therm, using EPS boards as the base panel. The IQ-Therm differ from normal EPS boards as it contains a large number of holes drilled into the board forming a grid with a distance of approximately 70-80mm between holes. A highly capillary active material is then filled into the holes of the board, which allow for the capillary active properties of e.g. a calcium silicate board while maintaining the low thermal conductivity of the EPS board. The setup was similar to that of models F-I, however with the small exception of replacing the calcium silicate board with the IQ-Therm board. [129] This setup was denoted with the model ID "J".

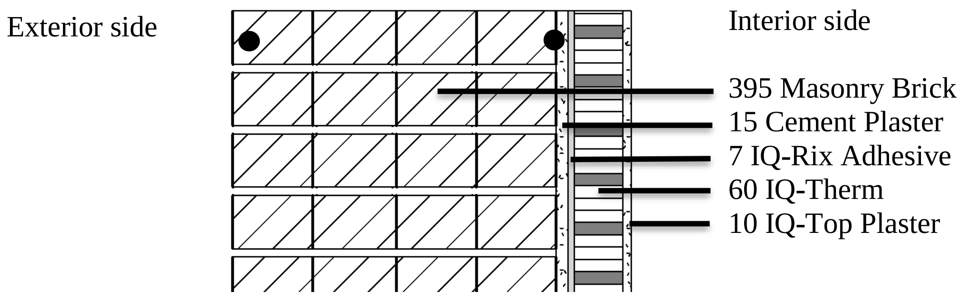


Figure 14: Wall Model J (Illustration by the author)

Assemblies ten and eleven were both capillary active solutions using autoclaved aerated concrete blocks from YTONG (YTONG multipor and YTONG South Aerated Concrete), a type of lightweight concrete with low thermal conductivity. The assemblies consisted of a capillary active mortar layer, next the YTONG blocks, and lastly a capillary active top plaster. [85] These setups were denoted with the model ID “K” and “L”.

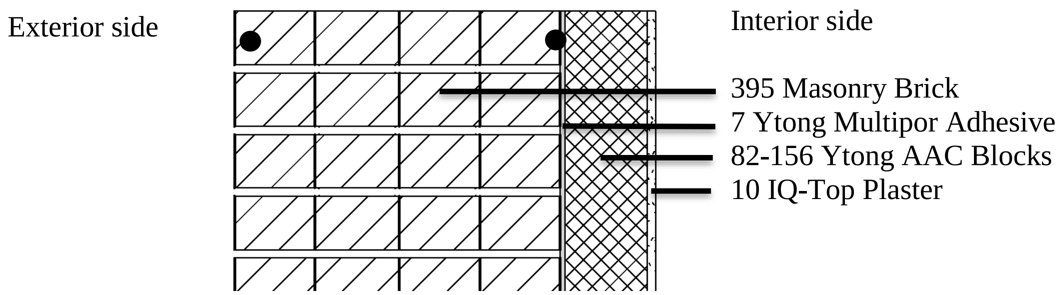


Figure 15: Wall Model K and L (Illustration by the author)

Assemblies twelve and thirteen were both a type of vapour tight solution using aerogel insulation (Aspen Aerogel Spaceloft). Setup twelve consisted of a layer of cement lime plaster applied to the existing wall, next the aerogel insulation blanket, then a vapour retarder, and lastly two layers of gypsum plaster. Setup thirteen consisted of a layer of cement lime plaster, next the aerogel insulation blanket, then a smart vapour retarder, and lastly a gypsum plasterboard separated from vapour retarder by an air cavity. [93] These setups were denoted with the model ID “M” and “N”.

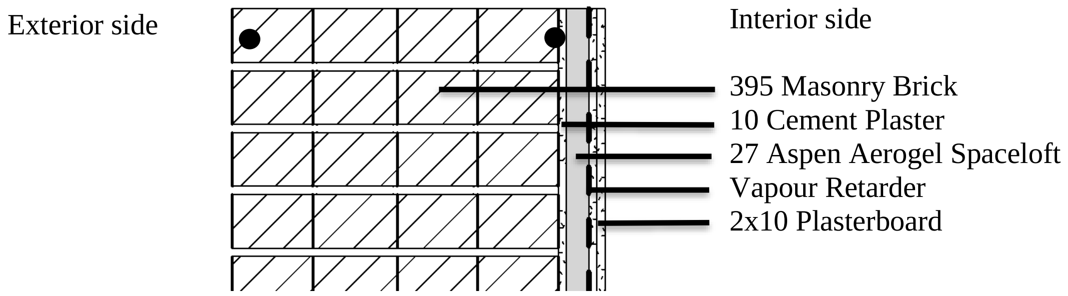


Figure 16: Wall Model M (Illustration by the author)

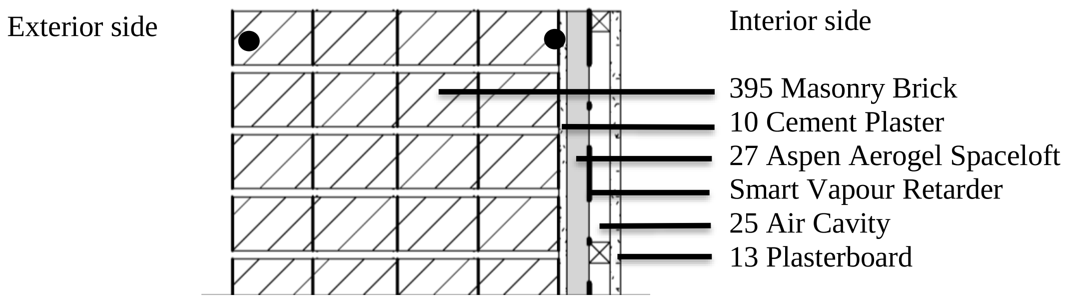


Figure 17: Wall Model N (Illustration by the author)

The fourteenth assembly was a type of vapour tight solution using the smart vapour retarder. The setup was similar to that of model B, however with the exception of replacing the normal vapour retarder with the smart vapour retarder. In addition to replacing the normal vapour retarder with the smart vapour retarder, the generic mineral wool was replaced by Isover glass wool. [96] [97] This setup was denoted with the model ID “O”.

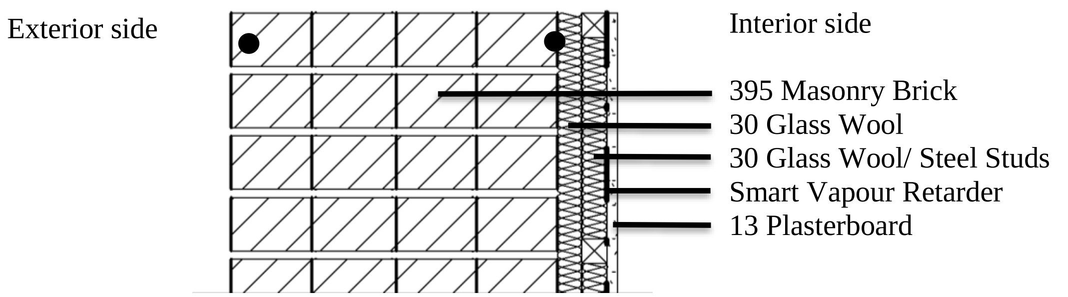


Figure 18: Wall Model O (Illustration by the author)

Assemblies fifteen and sixteen were both capillary active solutions using wood fibre insulation panels (Homatherm ID and Agepan THD). Setup fifteen consisted of a layer of cement lime plaster applied onto the existing wall, next the Homatherm ID panel, and lastly gypsum plasterboard [87]. Setup sixteen consisted of a layer of cement lime plaster, next an

OSB, then the Agepan THD panel, and lastly gypsum plasterboard [130]. These setups were denoted with the model ID “P” and “Q”.

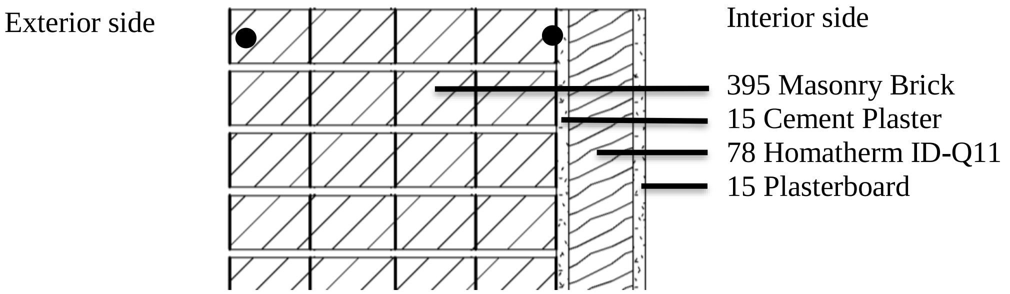


Figure 19: Wall Model P (Illustration by the author)

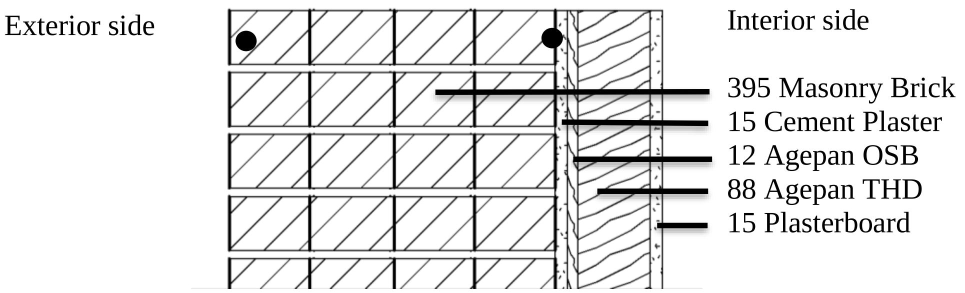


Figure 20: Wall Model Q (Illustration by the author)

The seventeenth assembly was a type of capillary active solutions using perlite insulation boards (StoTherm). The setup consisted of a type of capillary active plaster, next the perlite insulation board, then two layers of capillary active plaster, and lastly a type of capillary active top plaster [82]. This setup was denoted with the model ID “R”.

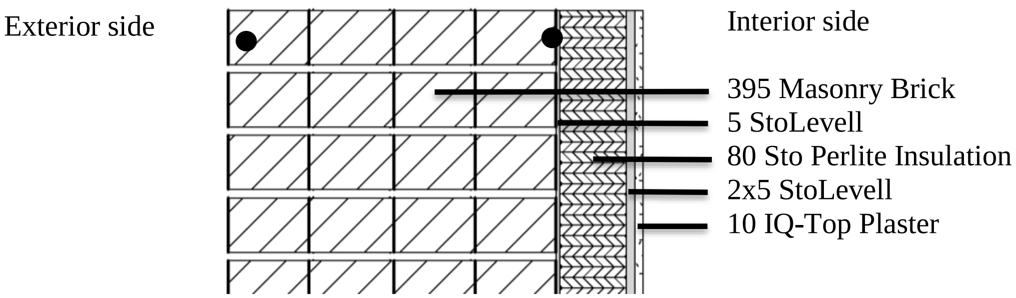


Figure 21: Wall Model R (Illustration by the author)

The eighteenth assembly was a type of vapour tight solution using a type insulating perlite plaster. The setup consisted of three layers of perlite plaster, applied over three times [99]. This setup was denoted with the model ID “S”.

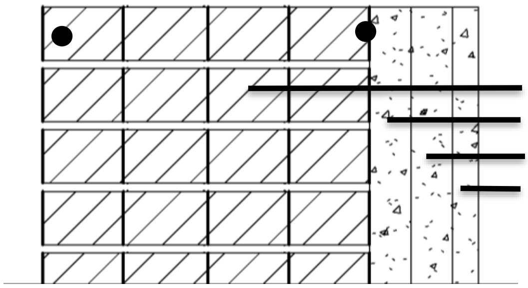


Figure 22: Wall Model S (Illustration by the author)

In addition to studying the different interior insulation assemblies, the impact of a water repellent coating applied to the exterior surface of the existing brick wall was studied. The impact of the water repellent coating was studied for both the base case wall and the 18 interior insulation assemblies. The water repellent coating was applied in WUFI by first reducing the thickness of the brick wall by 10 mm, then creating a copy of the brick wall with a thickness of 10mm, located on the exterior side. The material properties of this 10 mm thick brick part were then edited. First the Liquid Transport Coefficients for suction and redistribution were set to "generate" (a checkbox option within WUFI). Then the Water Vapour Diffusion Resistance Factor (µ-value) and Water Absorption Coefficient (A-value) were set according to the given material properties of the water repellent coating. This method for applying a water repellent coating was carried out according to the 2014 WUFI Tutorial on how to handle typical constructions in WUFI [126].

After simulating all 19 assemblies towards North and South, the most critical orientation was chosen for further assessment, and a water repellent coating was applied to the exterior surface of the wall assemblies. The chosen type of water repellent coating, was a transparent thick-layered siloxane coating with highly water repellent properties (Silancolor Tonachino). The water repellent coating had following material properties: a water vapour diffusion resistance factor of 178, a resistance to passage of vapour (S_d-value) of 0.267 m, and a Water Absorption Coefficient of 0.002 kg/($m^2 \cdot s^{0.5}$) [131].

5.5.4 General WUFI inputs for the roof assemblies

In the same way as for the exterior wall assemblies, the climate data from Gothenburg as well as the indoor climate conditions according to EN 15026 were used. However, in contrast to the exterior wall assemblies, the orientation for the roof assemblies was set according to their correct orientation, and not towards north or the prevailing direction of driving rain (south).

As mentioned earlier, the existing buildings had three different roof constructions, which are listed below:

- Bitumen cladding roof, with a 0° inclination, which was set as South facing in WUFI. Denotes with the model ID “A”.
- Bitumen cladding roof, with a 4° inclination, which was set as East facing. Denotes with the model ID “B”.
- Copper cladding roof, with a 20° inclination, which was set as West facing. Denotes with the model ID “C”.

Regarding the surface transfer coefficients, the exterior- and interior heat transfer resistance were set to 0.0526 $m^2 \cdot K/W$ and 0.125 $m^2 \cdot K/W$ respectively. The short-wave radiation absorptivity for model A and B was set to 0.88 as predefined for bituminous roofing felt, and for model C the value was set to 0.5 as predefined for green oil paint, assumed to be similar to that of the copper green colour. The S_d-values for model A and B was set to 300 m as predefined for bituminous roofing felt with PVC, and for model C the value was set to 50 m as predefined for aluminium cladding, assumed to be similar to that of the copper cladding. In addition to the before mentioned changes to the surface transfer coefficients, the adhering fraction of rain was set to zero for all the constructions. The remaining coefficients were kept as default. It should be noted that since the S_d-value and adhering fraction of rain were changed in the surface transfer coefficients dialog, then there is no need to set a designated cladding layers (bitumen felt or copper siding) in the assembly dialog. This is also the reason why the cladding layers are not mentioned in the following section describing the roof assemblies.

The initial moisture and temperature conditions within the wall construction were kept as default, which was relative humidity at 80 % and a temperature of 20 °C.

5.5.5 Roof assemblies

The three WUFI base case roof assemblies were created using the layers mentioned in Table 1, and the material specifications are shown in Appendix A. The assemblies for all three models were designed based upon the drawing material and the given u-values for the roof constructions. Although it should be mentioned that a number of assumptions were made for model A, as the drawing material did not cover this roof construction very well. According to the drawing material, model A consisted of a approximately 270 mm thick load bearing concrete deck, which had exterior insulation and bitumen felt cladding. Despite providing the material layers, and the thickness of the concrete deck, no information regarding the insulation type and thickness were found in the given data. The only design guideline was the U-value for the roof constructions, and a small side note that the roofs were renovated in 2011.

Table 1: Base Case Roof Assemblies in WUFI

Model ID	Layer No.	Material layers (Exterior to interior)	Layer Thickness [m]	Total Thickness [m]	U-value [W/(m²·K)]
A	0	Bitumen felt cladding		0.664	0.1
	1	Mineral wool	0.180		
	2	Mineral wool	0.200		
	3	Vapour retarder S_d=100 m	0.001		
	4	Concrete Deck (C12/15)	0.270		
	5	Plasterboard	0.013		
B	0	Bitumen felt cladding		0.276	0.269
	1	Mineral wool	0.020		
	2	Mineral wool between wood beams	0.110		
	3	Vapour retarder S_d=100 m	0.001		
	4	Air cavity with wood beams	0.118		
	5	Plasterboard	0.013		
	6	Vapour retarder S_d=100 m	0.001		
	7	Plasterboard	0.013		
C	0	Copper cladding		0.276	0.269
	1	60 minutes building paper	0.001		
	2	Plywood board	0.018		
	3	Air cavity with wood beams	0.136		
	4	Mineral wool with wood beams	0.034		
	5	Vapour retarder S_d=100 m	0.001		
	6	Plasterboard	0.015		

The following monitor positions were considered: Roof type A, the first monitor was placed between layer 1 and 2, while the second monitor was placed between layer 2 and 3. Roof type B, the first monitor was placed between layer 2 and 3, while the second monitor was placed between layer 3 and 4. Roof type C, the first monitor was placed between layer 2 and 3, while the second monitor was placed between layer 4 and 5. The purpose of the monitor positions was to measure the fluctuations in temperature and relative humidity during the year, at different places within the construction where moisture sensitive materials were located.

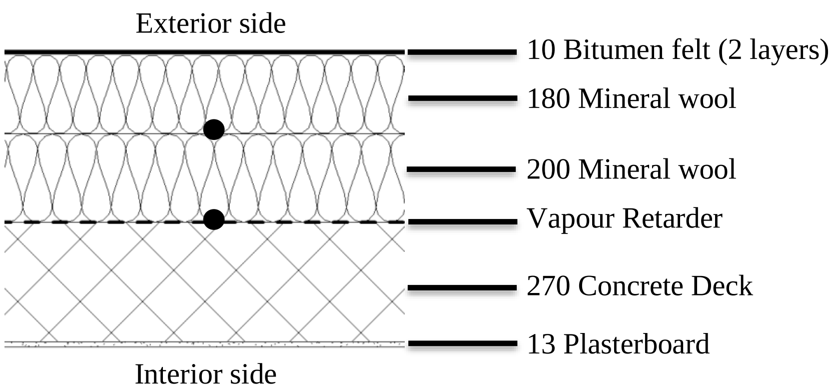


Figure 23: Roof Model A (Illustration by the author)

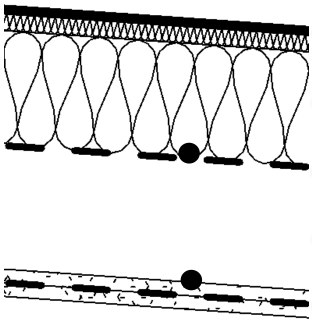


Figure 24: Roof Model B (Illustration by the author)

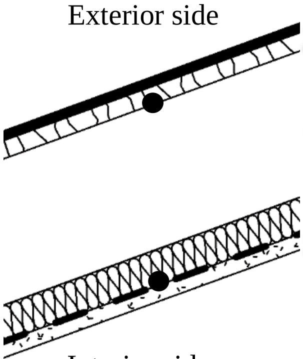


Figure 25: Roof Model C (Illustration by the author)

A total of five modified roof assemblies were chosen for this study, one with copper cladding and four with bitumen felt cladding. Information regarding the layers, thickness of layers, and thermal properties of the modified roof assemblies are shown in Table 2 below, and the material specifications are shown in Appendix A. The modified assembly with copper cladding was designed as a ventilated roof with an OSB, a layer of EPS insulation, and the copper cladding located on the exterior side of the ventilated air cavity. The purpose of the OSB and the EPS insulation located between the air cavity and the copper cladding, was to lower heat losses due to long wave radiation during night time, which in turn will reduce the risk of interstitial condensation within the air cavity, as described by Wallenten [132]. The modified assembly with copper cladding was denoted with the model ID “D”. The design of the first modified assembly with bitumen cladding was similar to model D, except that the short-wave radiation absorptivity and the S_d-value were changed to that of bitumen felt roofing. This bitumen assembly was denoted with the model ID “E”. The second and third assembly with bitumen cladding, were designed as warm roofs without a ventilated air gap, as according to SBi 224 – Fugt i Bygninger [6]. The second assembly was simulated with a regular vapour retarder, while the third assembly was simulated with a smart vapour retarder, the assemblies were denoted with the model ID “F” and “G”. The fourth assembly with bitumen cladding, was similar to model A, however, the mineral wool insulation material was replaced by a less moisture sensitive material, EPS insulation. This bitumen assembly was denoted with the model ID “H”.

Table 2: Modified Roof Assemblies in WUFI

Model ID	Layer No.	Material layers (Exterior to interior)	Layer Thickness [m]	Total Thickness [m]	U-value [W/(m²·K)]
D	0	Copper cladding		0.729	0.07
	1	EPS	0.070		
	2	Agepan OSB	0.020		
	3	Ventilated air cavity	0.040		
	4	Cement board	0.013		
	5	Mineral wool	0.225		
	6	Mineral wool between wood beams	0.245		
	7	Vapour retarder S_d=100 m	0.001		
	8	Mineral wool between wood battens	0.090		
	9	2x Gypsum board	0.025		
E	0	Bitumen felt cladding		0.729	0.07
	1	EPS	0.070		
	2	Agepan OSB	0.020		
	3	Ventilated air cavity	0.040		
	4	Cement board	0.013		
	5	Mineral wool	0.225		
	6	Mineral wool between wood beams	0.245		
	7	Vapour retarder S_d=100 m	0.001		
	8	Mineral wool between wood battens	0.090		
	9	2x Gypsum board	0.025		
F	0	Bitumen felt cladding		0.596	0.07
	1	Mineral wool	0.240		
	2	Mineral wool between wood beams	0.240		
	3	Vapour retarder S_d=100 m	0.001		
	4	Mineral wool between wood battens	0.090		
	5	2x Gypsum board	0.025		
G	0	Bitumen felt cladding		0.596	0.07
	1	Mineral wool board	0.240		
	2	Mineral wool between wood beams	0.240		
	3	PA-membrane SVR	0.001		
	4	Mineral wool between wood battens	0.090		
	5	2x Gypsum board	0.025		

H	0	Bitumen felt cladding		0.844	0.07
	1	EPS	0.280		
	2	EPS	0.280		
	3	Vapour retarder S_d=100 m	0.001		
	4	Concrete Deck (C12/15)	0.270		
	5	Gypsum board	0.013		

Similar to the base case assemblies, the purpose of the monitor positions was to measure fluctuations in temperature and relative humidity the in sensitive material layers. The monitor positions were as following for the modified roof assemblies:

Model D, first monitor between layer 4 and 5, and second monitor between layer 6 and 7.
Model E, first monitor between layer 4 and 5, and second monitor between layer 6 and 7.
Model F, first monitor between layer 1 and 2, and second monitor between layer 2 and 3.
Model G, first monitor between layer 1 and 2, and second monitor between layer 2 and 3.
Model H, first monitor between layer 1 and 2, and second monitor between layer 2 and 3.

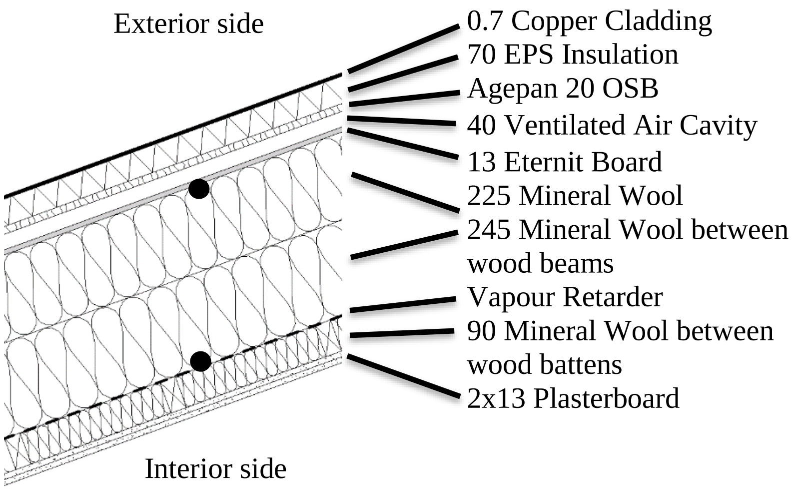


Figure 26: Roof Model D (Illustration by the author)

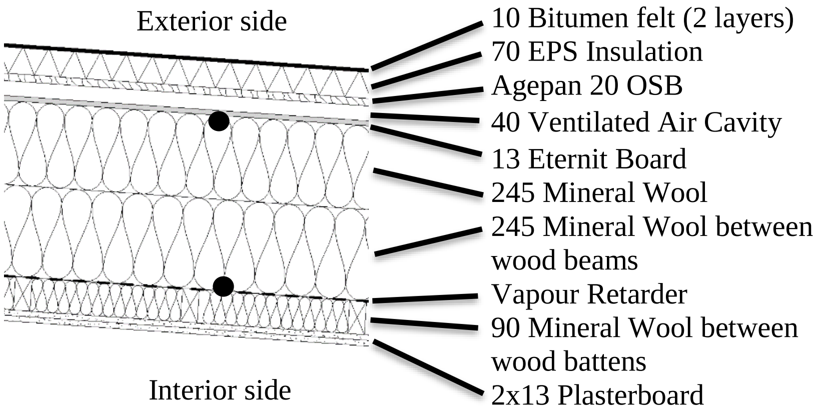


Figure 27: Roof Model E (Illustration by the author)

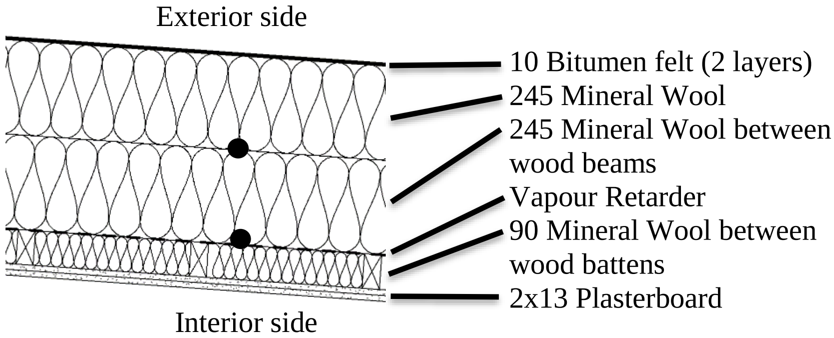


Figure 28: Roof Model F (Illustration by the author)

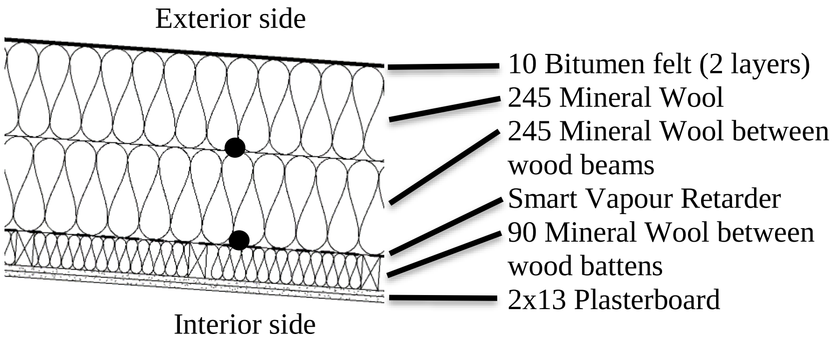


Figure 29: Roof Model G (Illustration by the author)

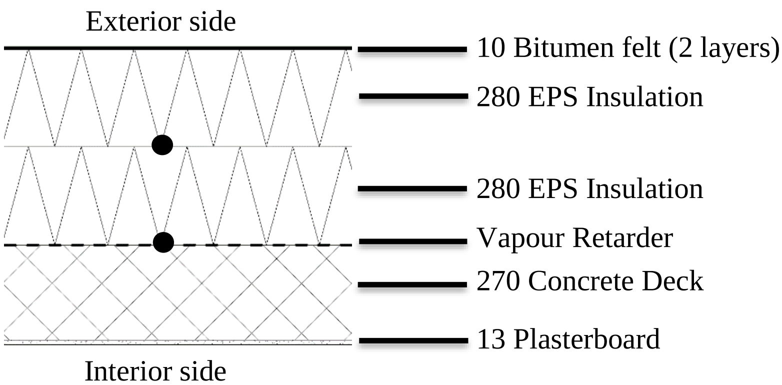


Figure 30: Roof Model H (Illustration by the author)

It should be noted that model D was simulated as West facing with a 20° inclination, while models E, F and G were only simulated as East facing with a 4° inclination. And granted that model H was the flat roof, this model was simulated as South facing with a 0° inclination.

5.5.6 Assessment of the simulation results

The assessment of the simulation results from the hygrothermal study was carried out using several Excel functions such as boxplot diagram as well as the “IF” and “AND” logical functions. These Excel functions were used to determine the changes in temperature, relative humidity, moisture content as well as to calculate the number of zero-crossings, which will be described more in detail in the following sections.

5.5.6.1 Boxplot diagram

The boxplot diagram or box-and-whisker diagram, is a tool commonly used for statistical analysis, which allow the user to display the distribution of numerical data based on the three quartiles Q_1, Q_2, and Q_3, as shown on Figure 31 below. The boxplot diagram was chosen for the presentation of the results of the 30-year periods, as this type of diagram is an easy yet powerful way to present a huge amount of data in just a few diagrams. The three quartiles divide the data set into four equal groups, where each group contains a quarter of the data values. The box part between Q_1 and Q_3 is called the “Interquartile range”, and it represents the middle 50% of the data value. The values below Q_1 represents the lower 25% of the data set, while the values above Q_3 represents the upper 25% of the data set. [133] [134]

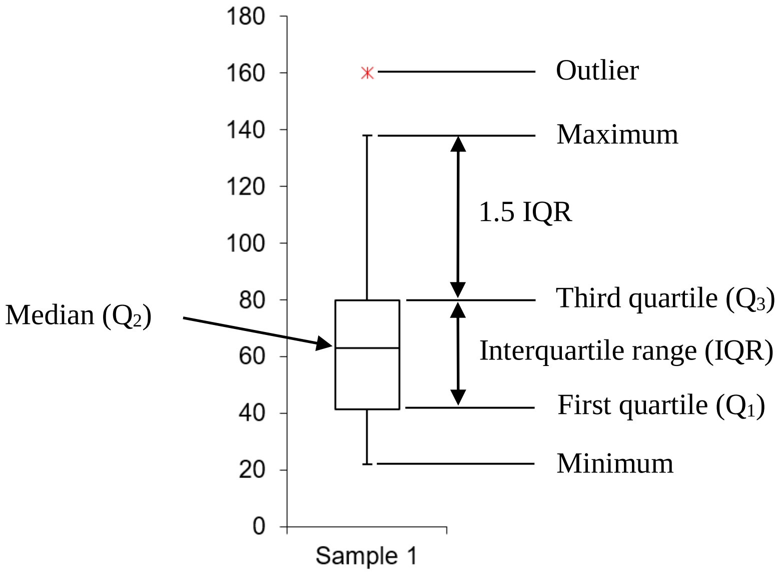


Figure 31: Example boxplot (Illustration by the author)

The lines extending vertically up or down from the box are called the “whiskers”, which represents the variability of the values located outside the interquartile range. The length of the whiskers may differ from case to case dependent on what type of results is required from the investigation. For the simplest of boxplots, the whiskers may be set to extent as far out as to the minimum- and maximum values of the data set. For the assessment of the WUFI results however, the whiskers were set to extent out to the last value which was less than or equal to 1.5 times the interquartile range in both the positive and negative direction. Any values located outside the range of the whiskers (in both positive and negative direction) are called “Outliers”. Outliers are values which are unexpectedly high or low compared to the majority of the values of the data set, which could indicate an error or simply an unexpected fluctuation in the data. Although outlier values often indicate an error or an unexpected fluctuation, it does not make the outlier values useless, on the other hand, the outlier values can at time be the most important finding of the investigation. [133] [134] Creating boxplot diagrams can be carried out using software like Matlab and Excel, for more information see [133] [135].

5.5.6.2 Freeze thaw damage

As mentioned earlier, a freeze thaw cycle occurs when the water content in the façade material exceeds the critical level of saturation, simultaneously with the temperature in the material cycling above and below 0 °C. Although the number of zero-crossings is considered as a good measure for estimating the risk of damages due to freeze thaw, it should be noted that in several studies, the lower temperature value was set to -5 °C for a zero-crossing to be taken into consideration. As a result of temperatures as low -5 °C or below, the water within the façade material will most certainly cause some extent of freeze thaw damage to the wall surface. [36] [34] For the purpose of this study, the lower temperature value for a zero-crossing to be taken into consideration was set to 0 °C, and the calculation period was set to 30 years.

The number of zero-crossings were calculated by importing the hourly values for temperature and moisture content in the façade material during the 30-year period into Excel, where the logical functions were used to assess the hourly values and determine the number of zero-crossings. The façade material used in this study was a solid brick masonry, and the free water saturation for this brick type was 190 kg/m^3. For this study three different levels of critical saturation were assessed, 30 %, 75 % and 90 % free water saturation. As a result, the critical moisture contents were 57, 142 and 171 kg/m^3 respectively. The first function would assess each set of hourly values, to determine if the moisture content would exceed the critical level of saturation at times where the temperature was below 0 °C. See Figure 32 below. After determining the presence of the preconditions for zero-crossings at each of the hourly values, the second function determined if an hourly value was to be considered as a new zero-crossing or not. As the first hourly value of a new zero-crossing was the only value to be considered in the calculation of the total number of zero-crossings. The second function counted a new zero-crossing as occurring, if the preconditions were met for the current hour simultaneously with the conditions not being met for the previous hour. Granted that the preconditions were not met for the previous hour, the current hour would then be considered as the beginning of a new zero-crossing and counted into the total number of zero-crossings, see Figure 33 below. In addition to calculating the number of zero-crossings, the boxplot diagrams were used for assessing the change in temperature and moisture content in the facade materials.

Freeze Thaw Cycle Calculation

	Free Water Saturation [kg/m3]:	190,00	
High	Critical Saturation Level [kg/m3]:	171,00	90%
Mid-High	Critical Saturation Level [kg/m3]:	142,50	75%
Low	Critical Saturation Level [kg/m3]:	57,00	30%

	Input Fields
	Result Fields

	Water Content Import		Temperature Import		High Crit. Saturation		Mid Crit. Saturation		Low Crit. Saturation	
	Hour no.	Water Content [kg/m3]	Hour no.	Temp [°C]	Frost Risk	No. of freeze thaw cycles	Frost Risk	No. of freeze thaw cycles	Frost Risk	No. of freeze thaw cycles
Base Line	**0,00**	**0,00**	**0,00**	**0,00**	**0**		**0**		**0**	
	0,00	18,00	0,00	20,00	0	0,00	0	0,00	0	0,00
	1,00	18,00	1,00	16,98	=IF(AND($C13>$E$4;$E13<0);1;0)				0	0,00
	2,00	17,99	2,00	15,66	IF(logical_test; [value_if_true]; [value_if_false])				0	0,00
	3,00	17,99	3,00	15,01	0	0,00	0	0,00	0	0,00
	4,00	17,98	4,00	14,85	0	0,00	0	0,00	0	0,00
	5,00	17,98	5,00	14,63	0	0,00	0	0,00	0	0,00

Figure 32: First function for calculating the number of zero-crossings [136]

Freeze Thaw Cycle Calculation

	Free Water Saturation [kg/m3]:	190,00	
High	Critical Saturation Level [kg/m3]:	171,00	90%
Mid-High	Critical Saturation Level [kg/m3]:	142,50	75%
Low	Critical Saturation Level [kg/m3]:	57,00	30%

	Input Fields
	Result Fields

	Water Content Import		Temperature Import		High Crit. Saturation		Mid Crit. Saturation		Low Crit. Saturation	
	Hour no.	Water Content [kg/m3]	Hour no.	Temp [°C]	Frost Risk	No. of freeze thaw cycles	Frost Risk	No. of freeze thaw cycles	Frost Risk	No. of freeze thaw cycles
Base Line	**0,00**	**0,00**	**0,00**	**0,00**	**0**		**0**		**0**	
	0,00	18,00	0,00	20,00	0	0,00	0	0,00	0	0,00
	1,00	18,00	1,00	16,98	0	=IF(AND(F13=1;F12=0);1;0)			0	0,00
	2,00	17,99	2,00	15,66	0	AND(**logical1**; [logical2]; [logical3]; ...)			0	0,00
	3,00	17,99	3,00	15,01	0	0,00	0	0,00	0	0,00
	4,00	17,98	4,00	14,85	0	0,00	0	0,00	0	0,00
	5,00	17,98	5,00	14,63	0	0,00	0	0,00	0	0,00

Figure 33: Second function for calculating the number of zero-crossings [136]

5.5.6.3 Mould growth

In the same way as with the results for freeze thaw cycles, boxplot diagrams were used for assessing the change in temperature and relative humidity at the interface between the existing wall construction and the new interior insulation, to determine the risk of mould growth due to interstitial condensation. In addition to assessing the results with boxplot diagrams, Folos 2D visual mould chart was also used for assessing the risk of mould growth.

The Folos 2D visual mould chart differ from most other mould charts as it accounts for the duration where the critical conditions are met, as well as a possible decline of the mould risk when the conditions are not met. In contrast to most other mould charts, the Folos 2D visual mould chart presents both the risk of mould growth as well as the temperature and relative humidity, for every hour of the year. Presenting the hourly results in this manner have proven beneficial in the process of determining what solutions may solve certain critical peak periods during the year with high risk of mould growth. The mould chart illustrated the risk of mould growth for each hour of the year with the $RH>RH_{crit}$ line on the graph. Through the $RH>RH_{crit}$ line, the severity of the critical conditions and the duration are visible. The higher the peak of the $RH>RH_{crit}$ line is, the higher the risk of mould growth. [137] For the purpose of this study, the LIM I [138] mould model was used for the Folos 2D visual mould chart, however any given mould model can be used in the Folos chart. After simulating the wall- and roof assemblies in WUFI, the hourly values for temperature and relative humidity were imported, and the Folos 2D visual mould chart would generate a series of graphs predicting the risk of mould growth within the different assemblies.

Besides using Folos 2D visual mould chart for visualizing the risk of mould growth, the hourly results from the Folos chart was also used to calculate the percentage of time where the preconditions for mould growth were met. As the calculated values would be a good approximation for the risk of mould growth between the different assemblies. Granted that an increase in the percentage of time where the preconditions are met, would also indicate an increased risk of mould growth.

5.6 Thermal bridging simulations

The thermal bridging simulations were carried out using the software HEAT2. Heat losses due to the thermal bridges in the building envelope were simulated, and the Ψ-value for each of the junctions between construction parts was obtained. Due to a number of software limitations, the Ψ-values were calculated through hand-calculations instead of obtaining the values directly through the software.

For the purpose of this study, only the wall and roof assemblies passing the criteria of the future climate scenarios in WUFI were taken further to the HEAT2 simulations. For the assemblies passing the criteria, four junctions were chosen: Window-wall, intermediate floor, roof eave, and wall corner (exterior). These four junctions were chosen for the HEAT2 simulations, as these junctions were the only ones available in all three energy simulation software. The four junctions for the three wall assemblies were all designed according to the same principles. Figure 34-37 show how the four junctions were designed in HEAT2 for wall assembly H. In connection with the design of the junctions, the length out each junction part were important in assuring accurate simulation results. The length should correspond to half of the distance to the neighbouring junction, as an example of this, the intermediate floor junction will be described, see Figure 34. For the two wall parts of the intermediate floor junction, the lengths were determined by taking half of the floor to ceiling height, for each wall part, while the floor length was determined by taking half of the interior building width. As for the material properties used in HEAT2, the λ-values for each of the materials were obtained from the material list for WUFI. In addition to the material properties, the temperature settings for the interior- and exterior side was set to 20 °C and -10 °C respectively, as a result, ΔT = 30 °C.

In the design of the construction details, new insulation was added on top of the concrete deck, as ceiling hanging as well as in the window sills/reveals, which were placed to lower the thermal bridging effect of the junctions further. By further lowering the thermal bridging effect of the junctions in this manner, the insulation will also help to lower the risk of moisture accumulating in the junction after the interior insulation. The junctions are always subject to higher exposure after an interior retrofit compared to the rest to the rest of the building envelope, due an increase in the heat flow through the thermal bridge caused by the interior retrofit.

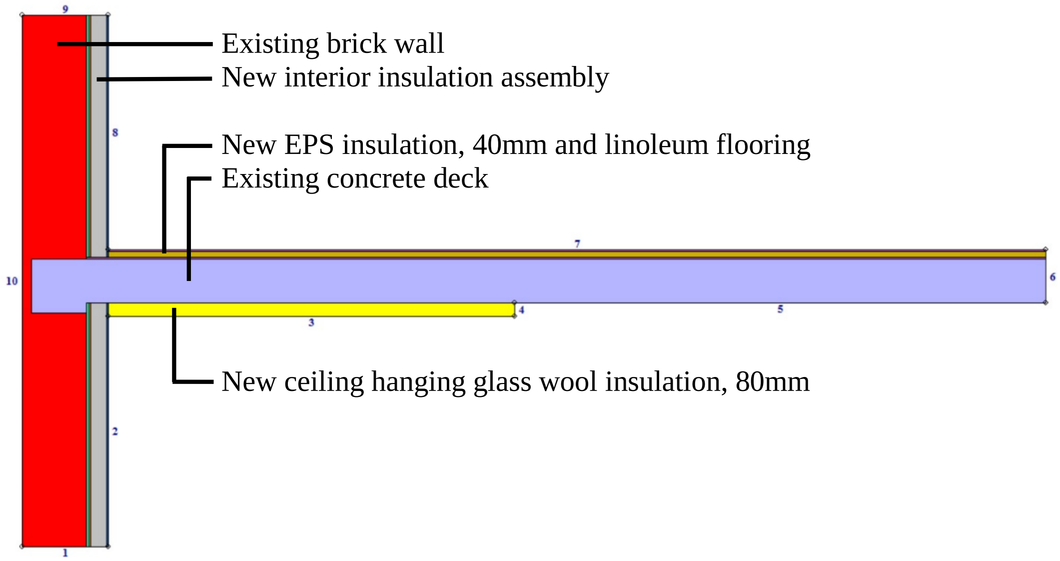


Figure 34: Intermediate floor junction, wall assembly H (Illustration by the author)

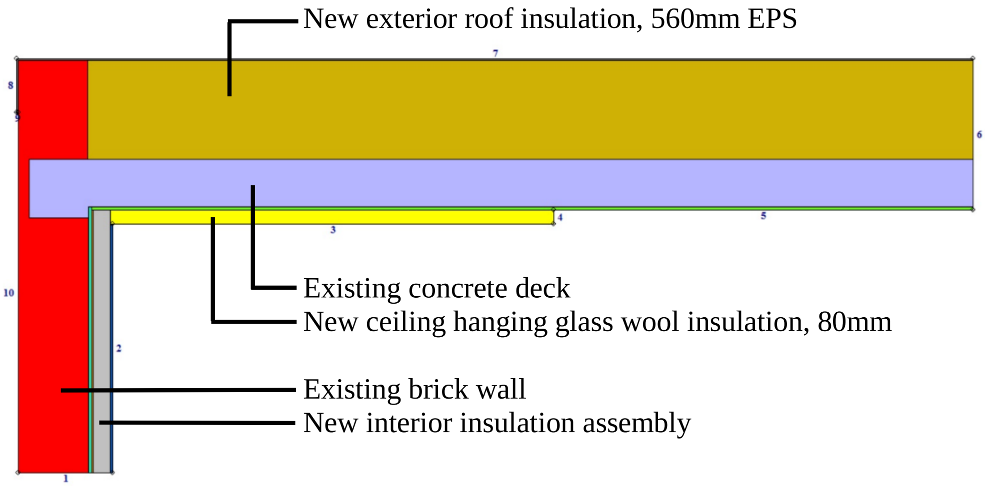


Figure 35: Roof eave junction, wall assembly H (Illustration by the author)

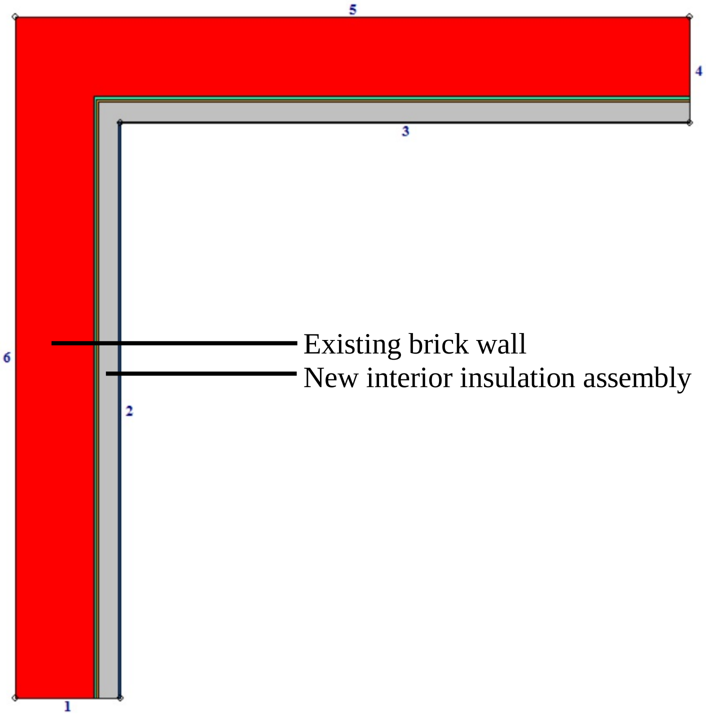


Figure 36: Wall corner (exterior) junction, wall assembly H (Illustration by the author)

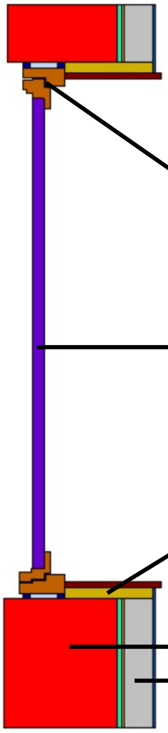


Figure 37: Window-wall junction, wall assembly H (Illustration by the author)

The HEAT2 steady-state simulation was carried out for the entire junction and the q_{tot} value was obtained. After simulating the entire junction, the junction was separated into two parts, and each part was then simulated by itself to obtain the q_1 and q_2 values. Only the intermediate floor junction was not separated into two parts. After simulating the individual parts, equations 1 was used for the roof eave (flat roof) and wall corner (exterior) junctions, while equations 2 was used for the intermediate floor junction. Unlike the other junctions, the thermal bridge around the window was carried out by simulating the glass- and wall parts separately, after simulating the entire junction. After simulating the glass- and wall parts, equation 3 was used to calculate the Ψ-value for the thermal bridge around the window.

$$\Psi=\frac{q_{tot}*(L_1+L_2)-(q_1*L_1+q_2*L_2)}{\Delta T*(L_1+L_2)} \quad [W/(m\cdot K)] \quad (1)$$

$$\Psi=\frac{q_{tot}-q_1}{\Delta T} \quad [W/(m\cdot K)] \quad (2)$$

$$\Psi=\frac{q_{tot}-(q_{glass}+q_{wall})}{\Delta T} \quad [W/(m\cdot K)] \quad (3)$$

After the Ψ-values were calculated by hand, they were included in the energy simulations, to account for the thermal bridges in the whole-building simulations.

5.7 Energy simulations

The energy simulations were carried out for both the A- and V-building, however, it should be noted, that the energy calculation as well as the input data was available only for the A-building. It was assumed that most of the input data would be similar or the same for both buildings, as both buildings were designed and built by the same architect within just a few years of each other. Also, as it was mentioned in section 5.3.1, the architect Klas Anshelm made use of similar construction solutions for all the buildings built at the technical university of Lund.

As mentioned earlier, the energy simulations were carried out in Design Builder, Honeybee, and IDA ICE. The initial idea behind carrying out the energy simulations in three different software, was for the author to acquire skills for the two latter software as well as to compare the simulation result from both the current and future climate simulations. However, due to compatibility problems, Design Builder and Honeybee were only used for the current climate simulations. The simulation results were nonetheless compared to support the correctness of the input data. The building models in Design Builder were modelled first, and the input data was calibrated according to the given material and reasonably estimated values were used for the missing input data. The calibration of input data was carried out to ensure proper inputs and results, as recommended by Sveby [139]. After achieving good results with given and reasonably estimated values, the other building models in Honeybee and IDA ICE were modelled with the same inputs to obtain comparable results. Furthermore, it should be noted that Appendix C contains a comprehensive explanation of the Honeybee simulation script.

5.7.1 Constant parameters

Throughout the energy performance study several parameters were kept constant such as location, model geometry, HVAC properties, schedules and zone load, as altering these parameters were not within the scope of this study. The constant parameters will be described in detail in the following sections.

5.7.1.1 Location, orientation and surrounding conditions

The A-building was located at longitude 13.2106436 latitude 55.7137624, and the V-building at longitude 13.2093095 latitude 55.7125368. Both buildings were oriented directly north to south, with the two large facades facing east and west. Regarding the surrounding conditions, several buildings of two to six storeys were located with 100-200 m of both the A- and V-building. Parking areas were located on the eastern side right next to both building with low vegetation of less than five meters of height, while on the western side were located green spaces. The green space west of the A-building contained large trees of more than 15-20 m of height, some located within 20 m from the south-western part of the A-building, and these same trees were also located within 20 m from the north-eastern part of the V-building. Figure 38 and Figure 39 below show the location of the A- and V-building and their surrounding conditions from an aerial view. As a result of the proximity of the nearby buildings and the surrounding conditions, the terrain setting were set to city scape for the energy simulations.

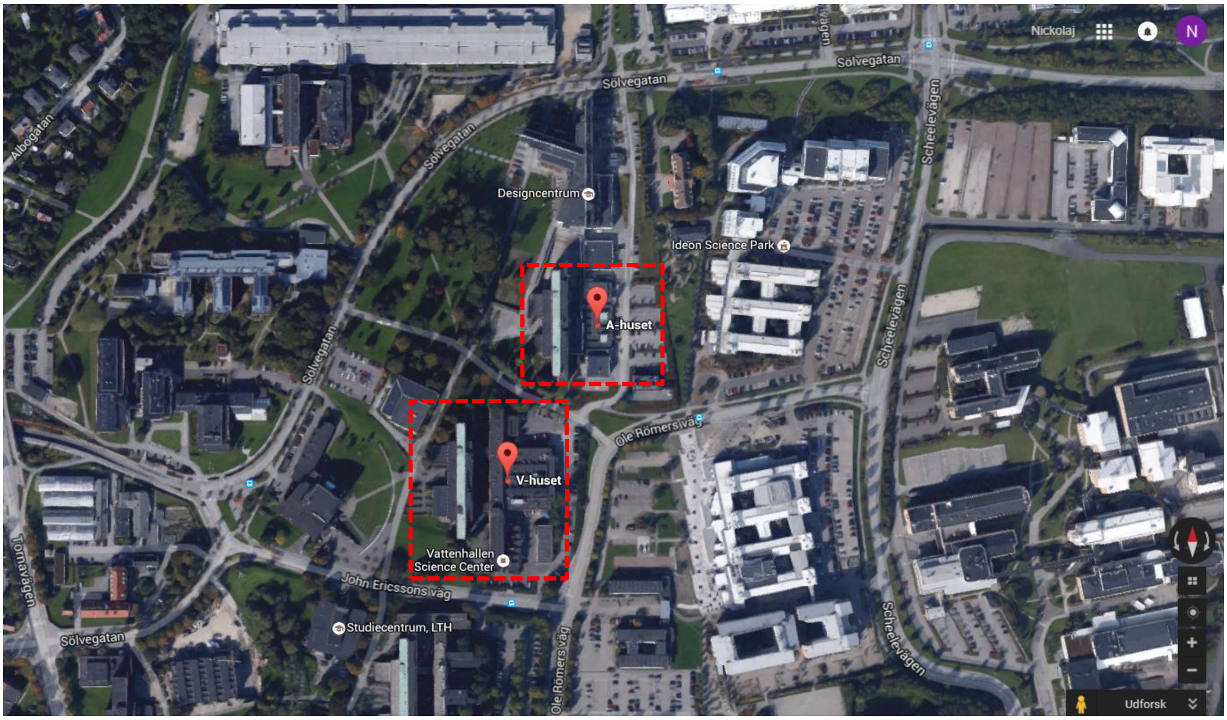


Figure 38: Aerial view 1 [162]

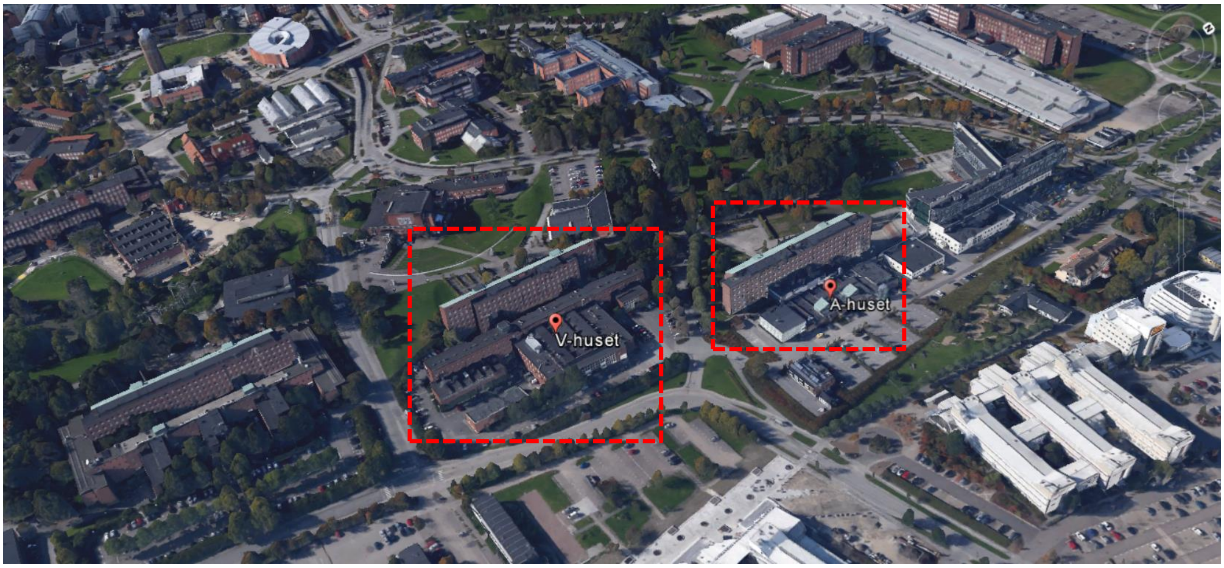


Figure 39: Aerial view 2 [162]

5.7.1.2 Model geometry

The building models for both the A- and V-building was created in Sketchup based upon the given drawing material, and then exported to the simulation software. 3D representations of the two buildings can be seen on Figure 40 below. The different colours on the 3D representation represents the different construction parts. Yellow colour represents the exterior walls, dark grey represents the roofs, pink represents the basement walls and basement floors, blue represents windows, and orange represents the interior floors.

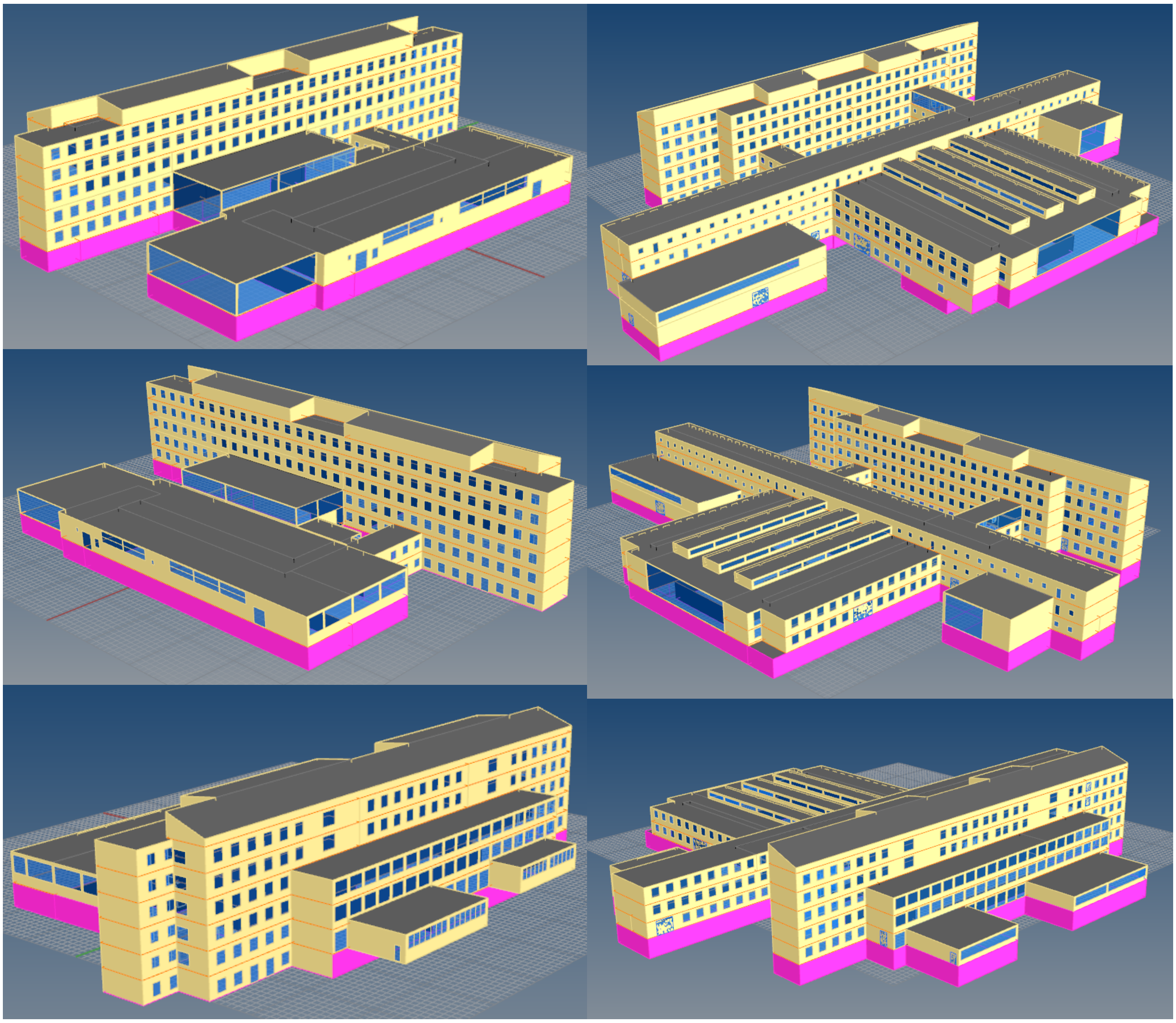


Figure 40: A-Building (left) and V-Building (right) (Illustration by the author)

The A-building consisted of three parts, the tall six storey office and classroom building on the west, the one storey laboratory building on the east, and new one storey exhibition hall in between. The floor to floor height for the A-building was in general set to 3.3 m with a few exceptions such as the basement level was set to 3.8 m, the laboratory building was set to 4.8

m, the auditoriums was set to 3.9 m, and the exhibition hall was set to 6.6 m. It should be noted that the sixth floor of the tall building was set entirely as HVAC room, as according to the drawing material. The total floor area of the A-building was 13570 m^2, and the building volume 45850 m^3. The building had 14990 m^2 of envelope area, where 3925 m^2 was roof area, 3920 m^2 slab on ground, 1700 m^2 windows, 1310 m^2 basement walls, and the remaining 4135 m^2 was exterior walls above ground. The V-building consisted of two parts, the tall six storey office and classroom building on the west, and the one to three storey laboratory building on the east. The floor to floor height for the V-building was in general set to 3.3 m with the exception of the lower basement level was set to 3.0 m, the basement level was set to 3.8 m, a few of the laboratory buildings was set to 6.6 m, and the apparat hall was set to 6.6 m. In the same way as for the A-building, was the sixth floor of the tall building was set entirely as HVAC room. The total floor area of the V-building was 22630 m^2, and the building volume 84010 m^3. The building had 24820 m^2 of envelope area, where 6835 m^2 was roof area, 8655 m^2 slab on ground, 2100 m^2 windows, 2215 m^2 basement walls, and the remaining 6815 m^2 was exterior walls above ground.

5.7.1.3 Windows

The windows were set according to the given drawing material (including size and placement) as well as from on-site pictures, see Figure 40 above for the window placement. The window to wall ratio for the given window geometry for the two buildings can be seen in Table 3. It was assumed that both the A- and V-building would have the same types of windows, with the exception of the new exhibition hall in the A-building, as this building came as a later addition. The window specifications are shown in Table 4. The A-building had a total window area of approximately 1700 m^2 while the V-building had approximately 2100 m^2.

Table 3: Window to Wall Ratio

Building Description	WWR Towards North [%]	WWR Towards South [%]	WWR Towards East [%]	WWR Towards West [%]
A-building	25	32.6	32.1	32.7
V-building	18.4	18.4	20.9	29.6

Table 4: Window Specifications

Location	Window Type	U-value [W/(m^2·K)]	T_{sol} [%]	SHGC [%]	T_{vis} [%]
Floor 0	Dbl. Clear, 6mm Glass/ 13mm Argon	2.511	0.604	0.704	0.781
Floor 1-5	Dbl. LoE (e2=.1) Clear, 3mm Glass/ 13mm Air	1.798	0.538	0.598	0.769
Exhibition	Trp. LoE Clear, 6mm Glass/ 13mm Air	1.202	0.21	0.31	0.455

Regarding the window frame, it was assumed that the frame to glass ratio would be around 30 %, and that the window frame U-value would be 2 W/(m^2·K).

5.7.1.4 Model infiltration

The model infiltration rate q_{50} was set to 1 l/s per m^2 exposed envelope area at a pressure differential of 50 Pa for both the A- and V-building, as according to the given material. With the exception of the exhibition hall for the A-building, which was set to 0.5 l/s per m^2 exposed envelope area, as stated in the given material. The infiltration rate corresponds to an average air chance rate of 0.97 ac/h at a pressure differential of 50 Pa. According to the Swedish building regulation (BBR) 2015, only the exhibition hall fulfilled the demand for the infiltration rate, which was maximum 0.6 l/s per m^2 exposed envelope area at a pressure differential of 50 Pa [140].

5.7.1.5 Interior heat gains

Regarding the calculation of the interior heat gains for occupancy, lighting and equipment, all rooms were divided into eight zone categories. Each zone category had different zone loads for lighting and equipment and/or different occupancy level.

It was specified in the given data, that the combined annual electricity intensity for lighting and equipment (including both operational and tenant electricity) would be 37 kWh/m^2. No specific information was provided for the actual zone loads and occupancy levels. As a result of not having any precise zone loads, it was necessary to match the given electricity intensity with the electricity intensity within Design Builder, Honeybee and IDA ICE, to ensure that the interior load would be comparable. To do this, the zone loads for lighting and equipment in each zone were first set according to the default "activity templates" from the templates library within Design Builder. The zone loads from each template were then scaled down, until the combined electricity intensity for lighting and equipment within the simulation software would match that of the given data. In the same way as with the zone loads, also the occupancy level for each zone category was based upon the activity templates from Design Builder. But unlike the zone loads, an assessment was carried out for each of the floor plans for the two buildings, regarding the zone areas under each zone category, to determine how many occupants would occupy each zone, and the occupancy level was then adjusted accordingly. The final zone loads and occupancy levels used for the energy simulations are shown in Table 5.

Table 5: Zone Loads and Occupancy Levels

Zone Category	LPD [W/m^2]	Equipment Load [W/m^2]	Occupancy Level [people/m^2]
Auditorium	3.5	1	0.25
Cell Office	3.5	6	0.04
Circulation	3.5	1	0.01
Classroom	3.5	4	0.16
Computer LAB	3.5	27	0.16
HVAC Room	3.5	38	0.1
Workshop (Small scale)	3.5	16	0.04
Workshop (Large scale)	3.5	4	0.04

5.7.1.6 Zone schedules

In the given data it was stated that the office part of the buildings would be occupied in the period 08:00 until 17:00 on week days, and that the all other areas would be occupied in the period 08:00 until 20:00 on week days. All zones of the building would be considered as unoccupied during weekends and holidays. In addition to the normal occupancy house, it was described that the auditoriums would be unoccupied during all of January month as well as in the summer holiday.

Based on this information, six different schedules were created for each zone category (Lighting, Equipment, Occupancy, Heating, Cooling and Mechanical Ventilation), and the schedules were build up as what is known as “fraction” schedules” or “compact schedules” [141].

The following zone categories: Computer LAB, Workshop Small Scale and Workshop Large Scale, all used the schedules for the classroom zone, as the occupant behaviour for these zones categories were assumed to be very similar to that of the classroom zone. Table 6 show the schedules assigned to each zone category, and Appendix D-I show in detail how the schedules have been build up. In addition to the zone schedules, a holiday schedule was created, containing a list of holidays that would be applied to all the zone categories, and as a result of the holiday schedule, the zones would be considered as unoccupied on these days, see Appendix J.

To ensure a reliable comparison between the three energy simulation software, the schedules were constructed in Design Builder, and then the hourly values within each schedule were exported to an excel sheet. From the excel sheet, the hourly values for each of the zone schedules were further imported into Honeybee and IDA ICE.

Table 6: Zone Schedules

Zone Category	Lighting Schedule	Equipment Schedule	Occupancy Schedule	Heating Schedule	Cooling Schedule	Mechanical Ventilation Schedule
Auditorium	Auditorium	Auditorium	Auditorium	Auditorium	Auditorium	Auditorium
Cell Office	Office	Office	Office	Office	Office	Office
Circulation	Circulation	Circulation	Circulation	Circulation	Circulation	Circulation
Classroom	Classroom	Classroom	Classroom	Classroom	Classroom	Classroom
Computer LAB	Classroom	Classroom	Classroom	Classroom	Classroom	Classroom
HVAC Room	HVAC	HVAC	HVAC	HVAC	HVAC	HVAC
Workshop (Small)	Classroom	Classroom	Classroom	Classroom	Classroom	Classroom
Workshop (Large)	Classroom	Classroom	Classroom	Classroom	Classroom	Classroom

5.7.1.7 Indoor air quality

The existing ventilation and conditioning system for the A-building was comprised of hot water radiators for heating, and seven AHUs units providing fresh air and cooling. The building was serviced by a VAV type HVAC system providing a total of 31.1 m^3/s of fresh air, and the specific fan power for the AHUs was calculated to be between 2.2 and 3.5 $kW/(m^3/s)$. Furthermore, the HVAC system was equipped with a heat exchanger with an efficiency of 60%. Due to simulation simplicity and lack of information regarding the input data, it was decided that the existing HVAC system would be simulated as a VAV type system with only one centrally located AHU, which would provide the total ventilation rate of 31.1 m^3/s. The VAV system used in this study was based on the "EnergyPlus Zone HVAC: Ideal Loads Air System" method. For the simulation models build in Design Builder and IDA ICE, the VAV system was simulated using a predefined VAV system template, which was determined to be suitable for the purpose of this study. In contrast to Design Builder and IDA ICE, the simulation software Honeybee did not have such a predefined VAV system template. As a result of the missing predefined VAV system template, a more simplified edition of the EnergyPlus Zone HVAC: Ideal Loads Air System method was used in Honeybee, as described in Appendix C.

In EnergyPlus, the Ideal Loads Air System is one of the simplest methods to model the HVAC system. The Ideal Loads Air System method is primarily intended for studying the building performance, without having to carry out a detailed modelling of the HVAC system. The Ideal Loads Air System act sort of like an "ideal conditioning unit", serving both heating, cooling and air supply with an efficiency of 100% (not to be confused with heat recovery efficiency) to meet the specified setpoint temperatures [142] [143].

Regarding the calculation of the minimum required ventilation rate for buildings in Sweden, the European standard EN 15251-2007 is used. Standard EN 15251-2007 states that for a category II building with very low pollution from building emissions (the school buildings fall under this category), a minimum ventilation rate of 7 l/s per occupant plus 0.35 l/s per m^2 floor area is required [144]. Granted the assumption, that the total amount of people in the A-building would be around 750 and with a floor area of 13570 m^2, the minimum required ventilation rate would be 9.51 m^3/s. With the given total of 31.1 m^3/s, the ventilation flow rate, besides the 7 l/s per occupant, was calculated to be 1.90 l/s per m^2 floor area.

With regards to the other ventilation settings, the given information stated that the AHUs would supply the fresh air at a temperature of 15 °C for all the zones, except for the auditoriums, where the air would be supplied at a temperature of 19 °C. An operative temperature of 21 °C during occupation hours and 18 °C when unoccupied, would then be maintained in the zones by the room units (hot water radiators). The total energy demand for space heating from the simulation software would then be the sum of the electric energy required by the heating coil in the AHUs, to heat up the outdoor air to 15 °C (19 °C for the auditoriums), plus the heating energy required by the radiators to maintain the operative temperatures. Although the cooling demand was not considered in this study, the given input data regarding the cooling system was still used, as to corroborate the simulation results for space heating. The cooling setpoint for the HVAC system was set to 27 °C for all the zones, except for the exhibition hall, during the occupied hours, and 30 °C during the unoccupied hours. The exhibition hall had a cooling setpoint of 25 °C during all hours. The cooling demand for the buildings were calibrated to meet the specified values from the given material. The calibration was carried out by altering the CoP for the heating systems. This option of altering the CoP was chosen due to the given material describing the cooling system as “free cooling”, having an annual cooling demand of approximately 1 kWh/m^2.

Although the A- and V-buildings are different, both in size and shape, it was assumed that the ventilation system for the V-building would be similar to the A-building. As a result, the V-building was also simulated with a ventilation flow of 7 l/s per occupant plus 1.94 l/s per m^2 floor area. It should be noted that in comparison with the A-building, the total ventilation rate for the V-building would be considerably bigger than the 31.1 m^3/s, as the total floor area of the V-building was approximately 70% bigger.

5.7.2 Variable parameters

Regarding the variable parameters in the energy performance study, only the building envelope and thermal bridges were altered. These two parameters will be described in detail in the following sections.

5.7.2.1 Building envelope

As mentioned earlier, very little information was provided regarding the existing building envelope, and that a number of assumptions were made regarding the material layers and thicknesses for each of the construction parts. The U-value for each of the construction parts as stated within the original energy calculation (performed three years prior to this study) are listed below. The assumptions regarding the material layers, thicknesses as well as thermal properties for the construction parts are shown in Appendix K.

Old building part:

- Slab on ground: 2.7 W/(m^2·K)
- Basement wall: 0.9 W/(m^2·K)
- Exterior wall - Brick (Floor 1-5): 1.2 W/(m^2·K)
- Exterior wall - Copper (Floor 6): 0.25 W/(m^2·K)
- Roof – Bitumen (Floor 1-5): 0.1 W/(m^2·K)
- Roof – Bitumen (Floor 6): 0.27 W/(m^2·K)
- Roof – Copper (Floor 6): 0.7 W/(m^2·K)

New Exhibition hall:

- Slab on ground: 0.1 W/(m^2·K)
- Basement wall: 0.9 W/(m^2·K)
- Exterior wall - Brick: 1.2 W/(m^2·K)
- Roof – Bitumen: 0.1 W/(m^2·K)

The only parameters which were changed for the building envelope, were the wall and roof U-values. As mentioned earlier, 18 wall assemblies and four roof assemblies were simulated, however only the assemblies passing the criteria of the future climate scenarios in WUFI were taken further to the HEAT2 simulations, and thus also further to the energy simulations.

Although the wall- and roof assemblies were designed with differences in layers and thicknesses, the assemblies were designed to have the exact same U-value. The U-value for the roof assemblies was 0.07 $W/(m^2 \cdot K)$, while for the wall assemblies it was 0.37 $W/(m^2 \cdot K)$. The choice of designing the assemblies with identical U-values was primarily done due to simplicity reasons for the energy simulations.

Despite retrofitting the wall- and roof constructs, it should be noted, that the infiltration rate was not lowered in the thermal simulations in response to the wall or roof retrofit, although some of the modified wall- and roof assemblies were considered as airtight. The possible change in the infiltration rate due to retrofitting was neglected, because of uncertainties regarding how much the retrofitting measures would actually lower the infiltration rate, as well as for simulation simplicity reasons.

5.7.2.2 Thermal bridges

No precise information existed regarding the thermal bridges for each of the construction parts. The thermal bridges were accounted for in the original energy calculation, by addition 30% to the transmission losses for the old building, and 20% to the transmission losses for the new exhibition hall. The correctness of the 30% and 20% additions to the transmission losses for the old and new buildings can be discussed, as the existing buildings were predominantly uninsulated, with the exception for the roof constructions and the new exhibition hall. The lack of insulation in the buildings lower the effect of the thermal bridges, as most of the construction part have equally poor thermal properties, thus an addition of 30 % and 20 % to the transmission losses may seem high.

The 30% and 20% additions to the transmission losses for the old and new buildings were removed in simulation cases using the modified wall- or roof assemblies, as the Ψ-values had been calculated for each of the junctions. Regarding the effect of the thermal bridges for those junctions that were not simulated, the typical values from IDA ICE were used within all three simulation software. As mentioned earlier, only the following junctions were simulated in HEAT2: Wall-window, intermediate floor, roof eave (flat roof), roof eave (incline roof), and wall corner (exterior).

5.7.3 Weather data and relative difference

The climate data sets used for the current- and future climate simulations were as described in section 5.4, where climate data sets for Malmo and Lund were used for the current climate simulation. While only climate data sets for Lund was used for the future climate simulations. The simulations were carried out using the “relative difference” method which have been previously studied by Nik et al. [145] [146].

5.7.4 Input verification with IDF-Editor

Simulation software utilizing the EnergyPlus engine will normally upon completing a thermal simulation, generate an IDF file containing all the model geometry and input data. The IDF file can in turn be imported directly into another simulation software also utilizing the EnergyPlus engine. Importing an IDF file from any given simulation software utilizing the EnergyPlus engine into the IDF-Editor software, allow the user to visualize the input data in a dialog interface, making data comparison between two or several simulation software relatively easy. Figure 41 shows an example of the dialog interface in the IDF-Editor software.

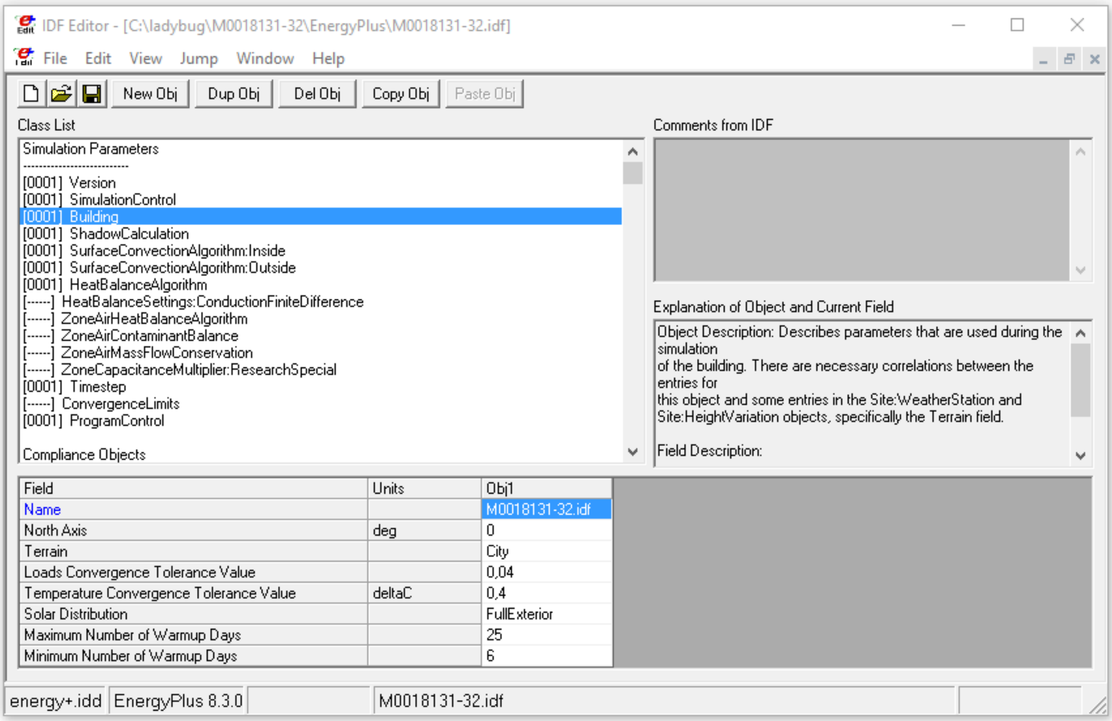


Figure 41: The dialog interface in the IDF-Editor [147]

For the purpose of this study, the IDF-Editor was used in the process of creating the energy simulation models in Design Builder and Honeybee. Both simulation models were assessing in the IDF files simultaneously, and differences between the two models were easily identified. Upon identification, the mistake would be fixed in the given simulation software.

5.8 Life cycle cost

The economic feasibility for the wall- and roof assemblies passing the criteria for the future climate scenarios in WUFI, were calculated through Life Cycle Cost (LCC) for a period of 50 years. The 50-year time period was chosen for the LCC calculations since this time period is a good estimation of the service life of a building, and have therefore been widely used for carrying out LCC and LCA [148]. The LCC included initial costs, point-in-time maintenance costs, yearly energy costs and yearly maintenance costs as well as yearly cost of lost floor space. All the costs in the LCC had to be calculated into net-present-value (NPV). The yearly costs for energy use, maintenance and lost floor space were calculated into NPV using equation 5 and 6, while the point-in-time maintenance costs were calculated into NPV using equation 3 and 4. Granted that all the costs were to be calculated into NPV, the interest rate as well as growth rates for district heating, maintenance and labour were required. The interest- and growth rates used in the LCC is shown in Table 7.

$$F = P(1+i)^N \quad \text{[SEK]} \quad (3)$$

$$P = F(1+i)^{-N} \quad \text{[SEK]} \quad (4)$$

$$A_1 = P(1+i)^1 \quad \text{[SEK]} \quad (5)$$

$$P=A_1 \frac{1-(1+g_r)^N(1+i)^{-N}}{i-g_r} \quad \text{[SEK]} \quad (6)$$

Table 7: Input data for LCC

Input Parameter	Interest Rate [%]	Growth Rate (District heating) [%]	Growth Rate (Maintenance) [%]	Growth Rate (rent) [%]	Growth Rate (Labour) [%]
Value	4	0.7*	2.5	1.7**	1.7***

* [149] ** [150] *** [151]

Material prices for the LCC were collected using the V&S price books [118], as well as from suppliers and hardware stores, if a product was not located in the price books. As the material prices were collected from Danish sources, it was necessary to use a price indexes to regulate the material prices into Swedish kronor (SEK). The ”Local Purchasing Power Index” for year 2016 was used, and the index values for Denmark and Sweden were 142.14 and 128.22 respectively [152]. The price regulation between the Danish prices and the Swedish prices were calculated using equation 7.

$$SEK = DKK \cdot (DKK\ index / SEK\ index) \quad (7)$$

Regarding the pricing of labour costs for the different construction tasks, a fixed hour price of 450 SEK/hour was used, and labour durations for numerous tasks were collected from construction management duration tables [153]. Maintenance interval of the surface materials, quantities, labour durations, prices, price sources for each of the materials used in the LCC are shown in Appendix L-M. In addition to the labour prices, also the energy cost for space heating was accounted for, by assigning a price of 0.912 SEK/kWh [154], as well as the cost for space loss. The cost for space loss was carried out by calculating the amount of lost floor space, which would be occupied by the new interior wall assemblies, by using the thicknesses of the assemblies. After calculating the lost floor space, a cost of approximately 1150 SEK/m^2 per year was assigned [155].

5.9 Life cycle assessment

Besides calculating the economic feasibility for the wall- and roof assemblies, also the environmental feasibility was determined. The environmental impact for each assembly was calculated though Life Cycle Assessment (LCA) and for consistency with the LCC a 50-year period was used. The software OpenLCA as well as Environmental Product Declarations (EPDs)[1], were used to determine the environmental impact for both the energy supply for space heating during the operational phase, and the environmental impact caused by the construction phase. In OpenLCA the ELCD (European reference Life Cycle Database) [156] database versions 3_elcd_3_1 [157] was used. As input for OpenLCA, a residential heating system for wood pellets was chosen as the source of energy, as this heating system resembled the district heating system supplying both the A- and V-building the most within the ELCD database. Electricity from hydroelectric power plants was chosen for the electricity source, as approximately 45% of the electricity in Sweden comes from hydroelectric power plants [30]. In addition to heating and electricity, also the environmental impact from car and truck transport during the construction phase was calculated, where a 22-ton lorry transport with a payload-distance[2] of 10 ton·km was used for the truck transport. For the car transport, a 7-ton lorry transport with a payload-distance[3] of 1 ton·km was used, as the ELCD database did not contain information for regular cars.

Based on the results from the energy simulations, the annual energy supply for space heating was summed up for the entire 50-year period and inserted into OpenLCA. In OpenLCA, the supplied energy was multiplied by the environmental emissions caused by district heating, to determine the total environmental impact caused by space heating.
The environmental impact caused by the construction materials for the wall- and roof assemblies, were based on material data from EPDs. As a result of the limited information provided by the EPDs, the study was restricted to consider only the following product stages: supply of raw materials, transport and manufacturing (cradle-to-gate).

Concerning the assessment of LCA results, the Life Cycle Impact Assessment (LCIA) method CML baseline was chosen and five environmental impact indicators were taken into consideration. The five environmental impact indicators included, Global Warming Potential for 100 years (GWP100) measured in kg CO_2 eq., Ozone Depletion Potential (OPD) measured in kg CFC-11 eq., Photochemical Oxidation Creation Potential (POCP) measured in kg C_2H_2 eq., Acidification Potential (AP) measured in kg SO_2 eq., and Eutrophication Potential (EP) measured in kg PO_4 eq. Information regarding the environmental emissions caused by the

[1] An EPD is an independently verified and registered documents, providing a standardized way of quantifying the environmental emissions of a product during the different life-cycle stages [163].
[2] For more information about payload-distance see [164].

operation- and construction phases included in the LCA calculations as well as the quantities are shown in Appendix N-O.

Besides the comparison between the five individual environmental impact indicators, the Dutch weighting method "Shadow Cost" was used for assessing the LCA results. The Shadow Cost method allowed for an easy-understandable comparison between the LCA cases, which would display multiple environmental impact indicators into one single indicator, where each environmental impact indicator would be assigned a cost. The cost per kg of substance in the LCA, is defined as the costs related to preventing the environmental damages, including all the necessary measured. The costs for each environmental impact indicator were multiplied by the quantity of each, and then summed up to one single cost for each LCA case. The ability to assign costs to multiple environmental impact indicators, but only present one single indicator is possibly the greatest advantage of using the Shadow Cost method to present the LCA results. As the Shadow Cost method allow for presenting LCA results for multiple cases containing multiple environmental impact indicators, in an easy-understandable while still very convincing manner for an audience who might not have a great knowledge regarding LCA and environment impact, such as stakeholders and occupants. [158] The cost per environmental impact indicator was obtained from [158]. The costs were given as euros per kg of substance, and the costs were converted into Swedish kronor (SEK) by using the currency converter Valutakurser.dk [159]. The currency conversion was carried out using the daily currency level on May 17th 2016, and the costs are shown in Table 8 below.

Table 8: Cost value per indicator in SEK

Environmental impact indicators	Substance	Cost value [SEK/kg]
Global Warming Potential for 100 years (GWP100)	CO_2	0.47
Eutrophication Potential (EP)	PO_4	37.40
Acidification Potential (AP)	SO_2	84.15
Ozone Depletion Potential (ODP)	CFC-11	280.50
Photochemical Ozone Creation Potential (POCP)	C_2H_2	18.70

6 Results

The following sub-chapters present the results for the hygrothermal simulations, thermal bridging simulations, energy simulations as well as the life cycle cost and life cycle assessment for the A- and V-building. For the hygrothermal simulations and energy simulations, the results for current climate scenario are presented first, followed by the results for the future climate scenarios. Additional results are found in Appendix P-Q.

6.1 Hygrothermal simulations

The present chapter presents the results of the hygrothermal simulations carried out in this study. The results for the risk of freeze thaw damage in the brick layer are presented first, followed by the results for the risk of mould growth. As mentioned in section 5.5.1, both the north orientation and the prevailing direction of driving rain were simulated to determine the worst orientation. This procedure was carried out both with and without the interior insulation as well as with and without the water repellent coating, however only for the current climate scenario. The results under this chapter are therefore presented by orientation.

The wall- and roof assemblies mentioned in section 5.5.3 and 5.5.5 will quickly be recapped below for better understanding the simulation results of the hygrothermal study presented in the following sections.

Wall assemblies:

- Model ID = A: Reference model
- Model ID = B: Traditional vapour tight mineral wool setup
- Model ID = C: Traditional vapour tight EPS insulation setup
- Model ID = D: Vapour tight VIP (Generic) and EPS insulation setup
- Model ID = E: Vapour tight VIP (Isover Vacupad) and EPS insulation setup
- Model ID = F: Capillary active Calsium Silicate AI setup
- Model ID = G: Capillary active Calsium Silicate Lüneburg setup
- Model ID = H: Capillary active Calsium Silicate Washington setup
- Model ID = I: Capillary active Calsium Silicate CaSi Masea setup
- Model ID = J: Capillary active IQ-Therm setup
- Model ID = K: Capillary active AAC (Ytong multipour block) setup
- Model ID = L: Capillary active AAC (Ytong south) setup
- Model ID = M: Vapour tight Aerogel insulation setup (no air cavity)
- Model ID = N: Vapour tight Aerogel insulation setup (air cavity and SVR)
- Model ID = O: Vapour tight glass wool setup with SVR
- Model ID = P: Capillary active wood fibre insulation (Homatherm) setup
- Model ID = Q: Capillary active wood fibre insulation (Agepan) setup
- Model ID = R: Capillary active Perlite insulation board (Sto) setup
- Model ID = S: Vapour tight Perlite insulating plaster setup

Roof assemblies:

- Model ID = A: Reference model (Flat bitumen felt roof consisting of exterior insulated concrete deck using mineral wool)
- Model ID = B: Reference model (Incline bitumen felt roof consisting of wood beams and mineral wool)
- Model ID = C: Reference model (Incline copper roof consisting of wood beams and mineral wool)
- Model ID = D: Incline ventilated roof consisting of wood beams, mineral wool, exterior OSB and EPS, and copper cladding
- Model ID = E: Incline ventilated roof consisting of wood beams, mineral wool, exterior OSB and EPS, and bitumen felt cladding
- Model ID = F: Incline unventilated roof consisting of wood beams, mineral wool, and bitumen felt cladding
- Model ID = G: Incline unventilated roof consisting of wood beams, mineral wool, SVR, and bitumen felt cladding
- Model ID = H: Flat unventilated roof consisting of exterior EPS insulated concrete deck

6.1.1 Wall assemblies: freeze thaw damage

As mentioned earlier, the risk of freeze thaw damage was determined by assessing the fluctuations of the temperature and water content at the first monitor position, approximately 20 mm from the exterior surface. The three critical levels of saturation assessed for the risk of freeze thaw damage were 57, 141, and 171 kg/m^3, corresponding to 30%, 70%, and 90% of the free water saturation.

6.1.1.1 North orientation

As shown in Figure 42-44, all the North facing wall assemblies experience an increase in the water content as result of the interior insulation in comparison with the reference case (model A). Despite the increase in the water content, all the wall assemblies do stay below the three critical levels of saturation, for the majority of the time (more than 75 % of the time). The vapour tight assemblies in general experience a higher increase in the water content (models B, C, D, E, and M) in comparison to the capillary active assemblies, with the exception of the assemblies with the smart vapour retarder as well as the insulating plaster (models N, O and S). Models N, O and S show a smaller increase in the water content, more similar to that of the capillary active assemblies. Although all the wall assemblies stay below the critical levels of saturation for the majority of the time, the outlier values shown in the boxplots do show, that the water content for most of the assemblies at times do exceed the lowest critical level of saturation of 57 kg/m^3. Of all the capillary active assemblies, the IQ-Therm assembly (model J), show the highest water content, passing 40 kg/m^3 more than 75 % of the time.

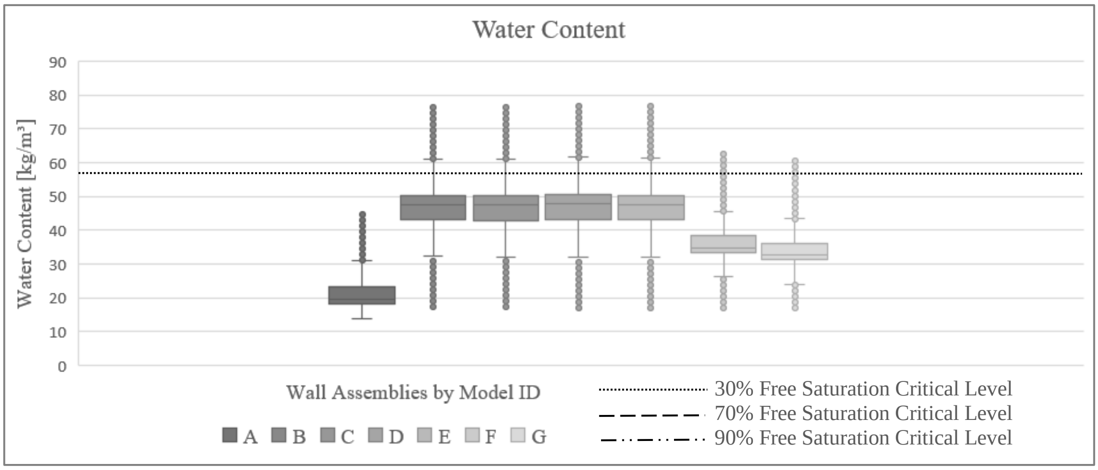


Figure 42: Water content in the wall assemblies, models A-G (North orientation)

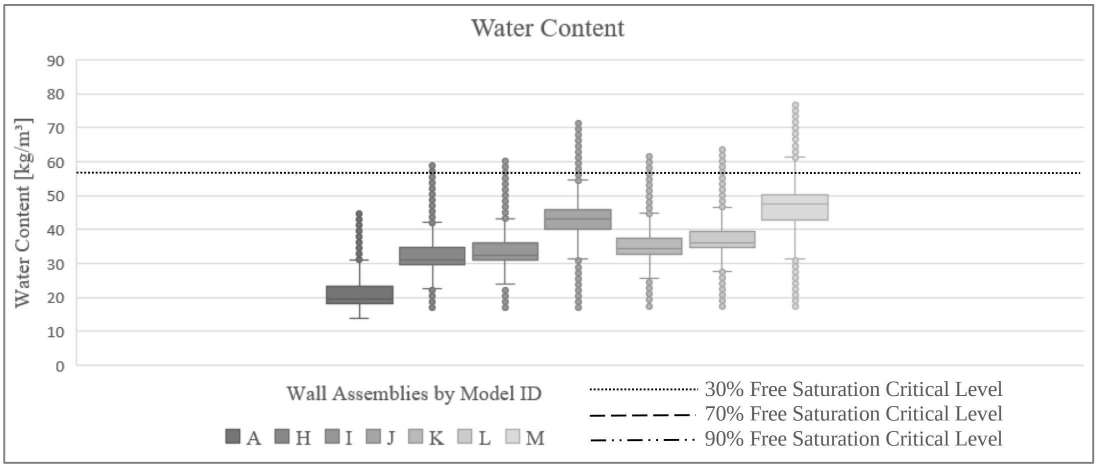


Figure 43: Water content in the wall assemblies, models A, H-M (North orientation)

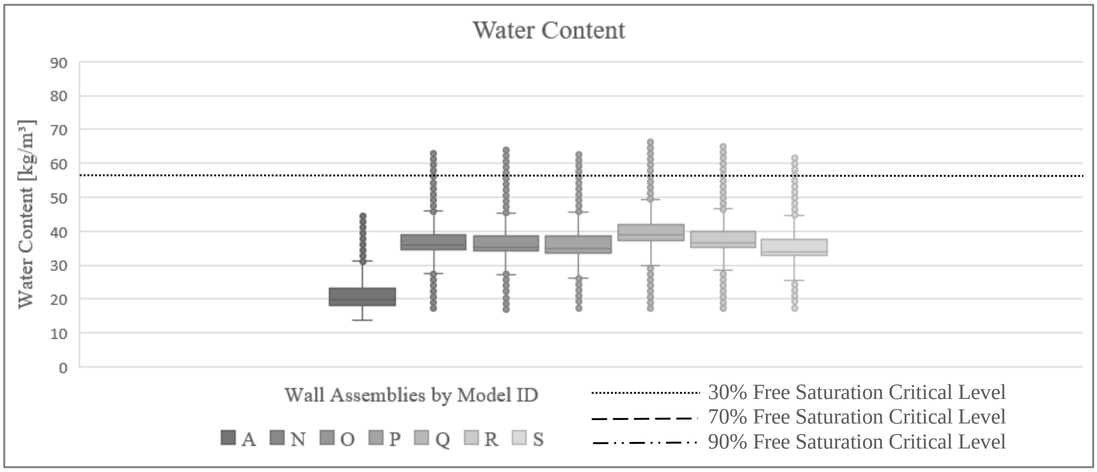


Figure 44: Water content in the wall assemblies, models A, N-S (North orientation)

Regarding the temperature at the first monitor position, 20 mm into the wall construction measured from the exterior side, Figure 45-47 show that all wall assemblies experience a slight drop in temperature due to the installation of the interior insulation, which are similar for all the assemblies. No single wall assembly differs from the others with regards to the temperature.

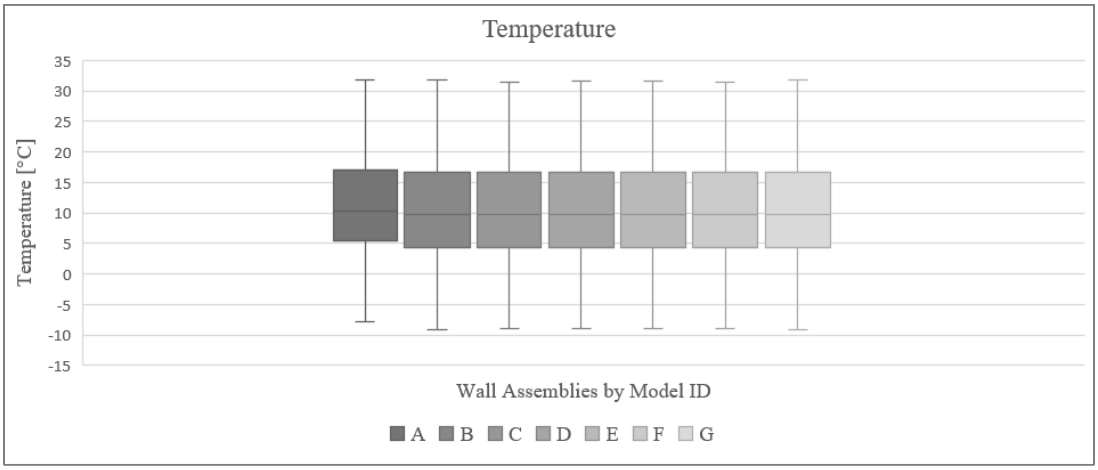


Figure 45: Temperature in the wall assemblies, models A-G (North orientation)

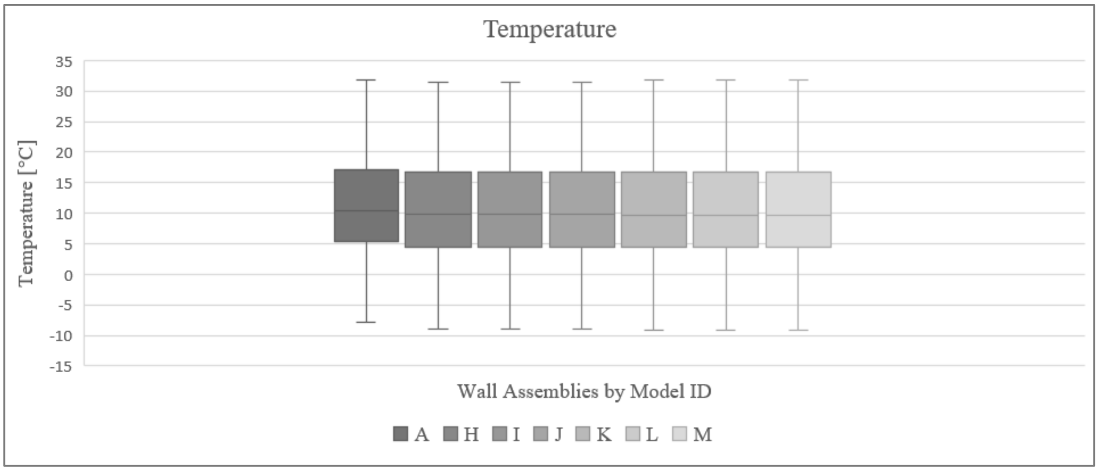


Figure 46: Temperature in the wall assemblies, models A, H-M (North orientation)

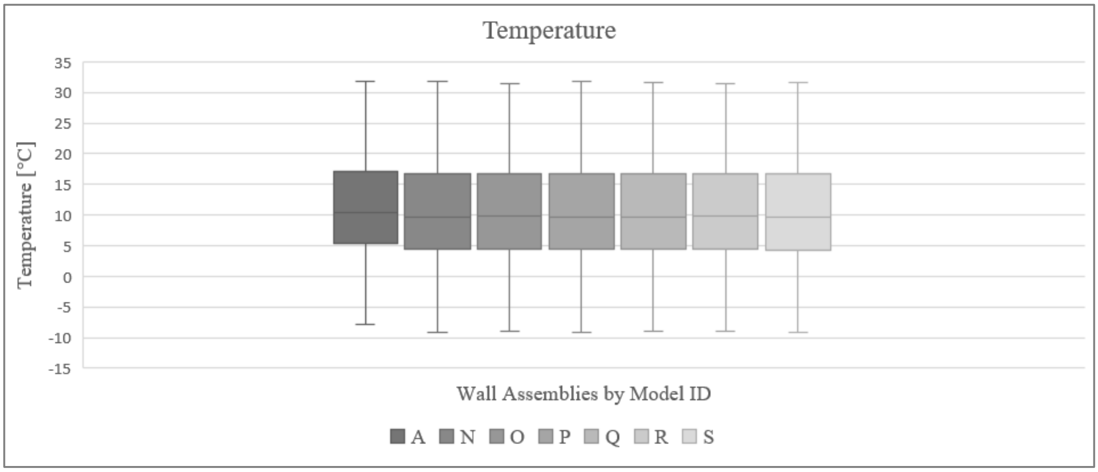


Figure 47: Temperature in the wall assemblies, models A, N-S (North orientation)

Besides plotting the simulation results into boxplot, the average values and standard deviation were calculated for each of the assemblies. The results for the moisture content and temperature are shown in Table 9. In the same way as with the boxplots, the average values and standard deviation show how the water content in the wall stay below the critical levels of saturation, as well as how there is a slight drop in the average temperature at the first monitor.

Table 9: Average and standard deviation for the water content and temperature

	Water Content [kg/m3]		Temperature [°C]	
Model ID	Average	Standard deviation	Average	Standard deviation
A	22	5	11.2	7.3
B	46	9	10.6	7.6
C	46	9	10.6	7.6
D	47	9	10.6	7.6
E	46	9	10.6	7.6
F	36	7	10.6	7.5
G	34	6	10.6	7.6
H	33	6	10.6	7.6
I	34	6	10.6	7.5
J	43	8	10.6	7.6
K	36	6	10.6	7.6
L	38	6	10.6	7.6
M	46	9	10.6	7.6
N	37	7	10.6	7.6
O	37	7	10.6	7.6
P	37	7	10.6	7.6
Q	40	7	10.6	7.6
R	38	7	10.6	7.5
S	36	6	10.6	7.6

After assessing the results using boxplots, the results were taken into the freeze thaw calculation sheet in excel to calculated the number of zero-crossing during the 30-year period. The assessment of the wall assemblies with North orientation in the freeze thaw calculation sheet showed, that there would be a very low risk of freeze thaw damages occurring, as the number of zero-crossings for all the wall assemblies was calculated to zero crossings during the 30-year period.

6.1.1.2 South orientation

In contrast to the North orientation, the South orientation show a large increase in the water content in all the wall assemblies in comparison to the reference case (model A), as shown in Figure 48-50. As a result of the large increase in the water content, there should also be an increased risk for freeze thaw damages to occur. In the same way as the North facing wall assemblies, the vapour tight assemblies (models B, C, D, E, M, N, and O) experience a higher increase in the water content, in comparison to the capillary active assemblies. But in contrast to the North orientation, for the South orientation both the capillary active wood fibre assemblies as well as the IQ-Therm assembly (models J, P, and Q) showed an increase in the water content similar to that of the vapour tight assemblies, reaching up to around 150 kg/m^3, where at the North orientation only the IQ-Therm assembly showed a higher increase in the water content. Another difference between the North- and South orientation, was the insulating plaster assembly (model S) which differed a lot from the other vapour tight assemblies. The insulating plaster assembly actually outperformed the capillary active assemblies in respect to maintaining a low water content, as the water content in the insulating plaster assembly stays relatively similar to that of the reference case (model A).

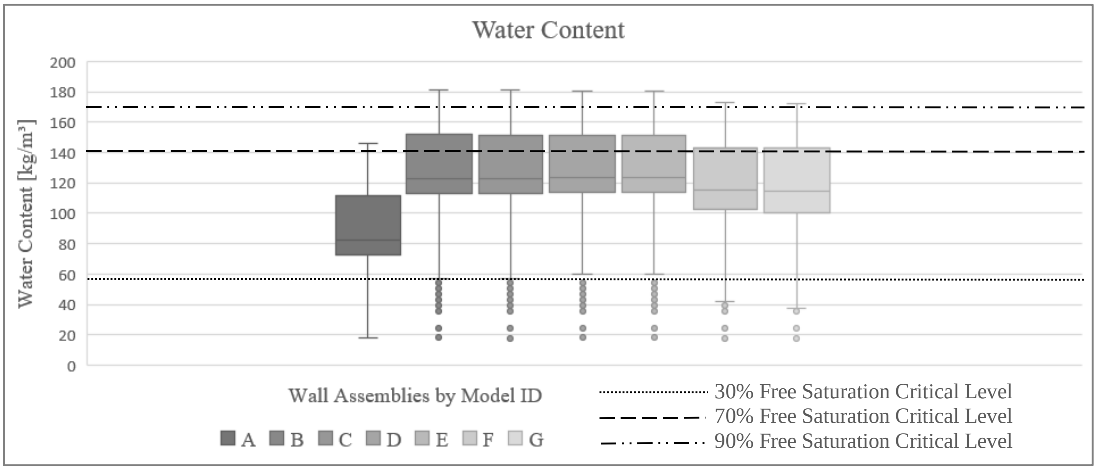


Figure 48: Water content in the wall assemblies, models A-G (South orientation)

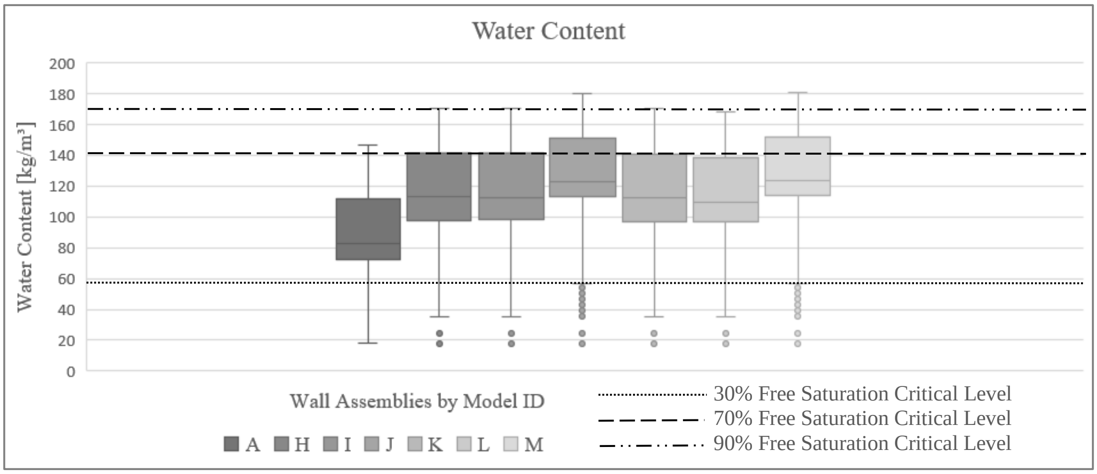


Figure 49: Water content in the wall assemblies, models A, H-M (South orientation)

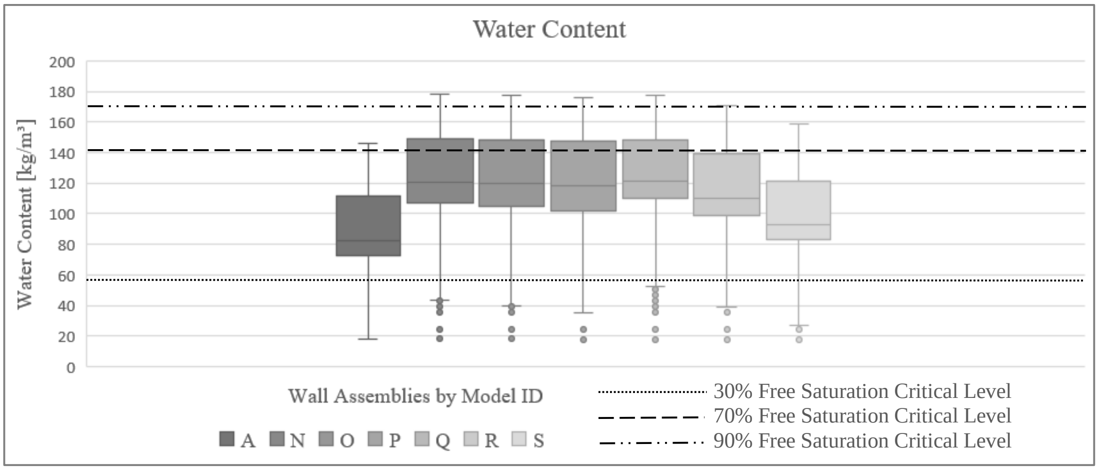


Figure 50: Water content in the wall assemblies, models A, N-S (South orientation)

As seen for wall assemblies with the North orientation, the results for the wall assemblies with the South orientation show a similar drop in temperature due to the installation of the interior insulation, where all the wall assemblies follow the same trend. See Figure 51-53.

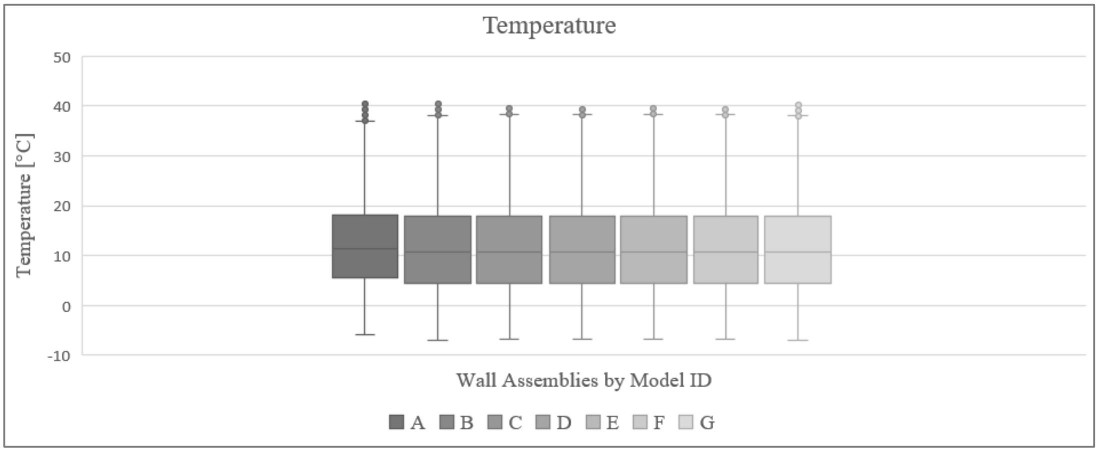


Figure 51: Temperature in the wall assemblies, models A-G (South orientation)

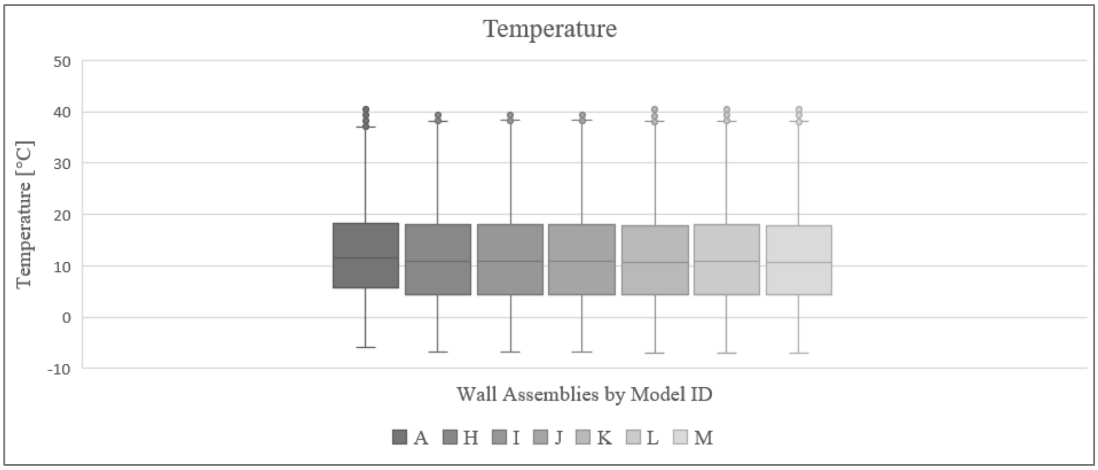


Figure 52: Temperature in the wall assemblies, models A, H-M (South orientation)

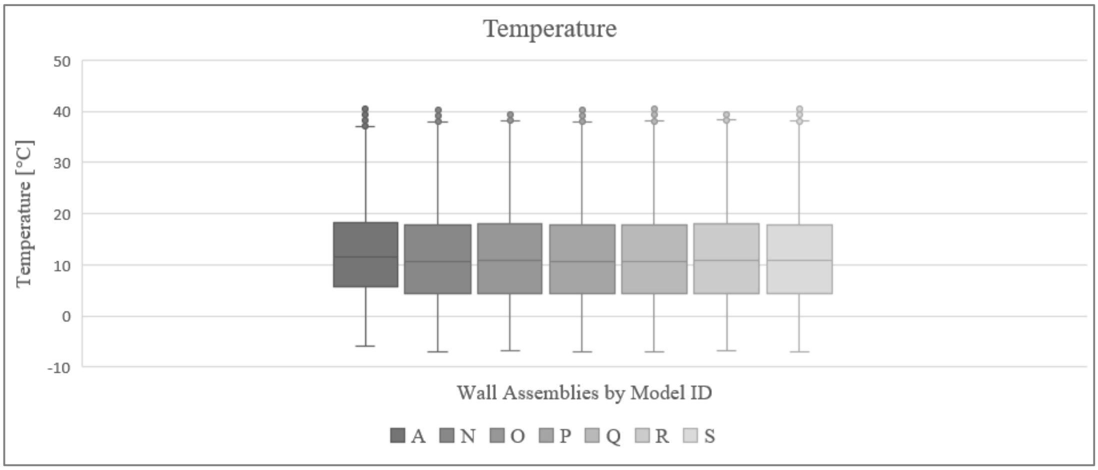


Figure 53: Temperature in the wall assemblies, models A, N-S (South orientation)

In the same way as for the North orientation, the average values and standard deviation were calculated for each of the assemblies. The results for the moisture content and temperature are shown in Table 10. Compared to the North orientation, the wall assemblies with the South orientation show a lightly higher average temperature, by approximately 1.2 - 1.5 °C. Also, as it was seen on the boxplots, the average water content show that the water content in all the South facing wall assemblies exceeds the lower critical level of saturation (57 kg/m^3), while the average value for all the assemblies stay below the medium- and high critical level of saturation (141 kg/m^3 and 171 kg/m^3 respectively). But despite the fact that the average values stay below the medium critical level of saturation, the standard deviation show that the water content in most of the wall assemblies will exceed this threshold occasionally.

Table 10: Average and standard deviation for the water content and temperature

	Water Content [kg/m3]		Temperature [°C]	
Model ID	Average	Standard deviation	Average	Standard deviation
A	91	26	12.6	8.6
B	130	25	11.8	9.0
C	131	25	11.8	8.9
D	131	24	11.8	8.9
E	131	24	11.8	8.9
F	122	25	11.8	8.9
G	121	26	11.8	9.0
H	119	26	11.8	8.9
I	119	26	11.8	8.9
J	130	25	11.8	8.9
K	118	26	11.8	9.0
L	116	26	11.9	9.0
M	131	24	11.8	9.0
N	127	26	11.8	9.0
O	126	26	11.8	8.9
P	123	27	11.8	9.0
Q	128	25	11.8	9.0
R	118	26	11.9	8.9
S	36	6	10.6	7.6

Granted the large increase in the water content in all the wall assemblies with the South orientation, the results from the freeze thaw calculation sheet showed a considerably higher risk of freeze thaw damages occurring. Not one assembly stayed clear from the risk of freeze thaw damages at all three critical levels of saturation. Besides the uninsulated wall assembly (model A), it was primarily a few of the capillary active assemblies as well as the insulating plaster (models F, G, H, I, K, L, P and S), which managed to stay risk free at the highest critical level of saturation, 90% free water saturation, furthermore, no assembly managed to stay below the medium critical level of saturation, 70% free water saturation, as shown in Table 11.

Table 11: Number of zero-crossing at different critical levels of saturation

	Number of Zero-crossings		
Model ID	90% of Free Water Saturation	70% of Free Water Saturation	30% of Free Water Saturation
A	0	0	541
B	143	867	1045
C	143	867	1043
D	143	867	1043
E	142	867	1043
F	0	637	1043
G	0	609	1073
H	0	607	1043
I	0	607	1043
J	113	864	1044
K	0	607	1073
L	0	577	1044
M	142	895	1103
N	84	833	1074
O	84	749	1043
P	0	637	1073
Q	84	861	1044
R	0	578	1043
S	0	347	1074

6.1.1.3 South orientation with water repellent coating

As the results showed that the South orientation was the most critical orientation, due to the high amounts of wind-driven rain. Further assessments for the risk of freeze thaw damage at the first monitor position was carried out for the wall assemblies with the South orientation. Further assessments were carried out with the application of a water repellent coating on all the wall assemblies, as mentioned in section 5.5.3.

As shown in Figure 54-56, the application of the water repellent coating on the wall assemblies with the South orientation, effectively eliminated the risk of freeze thaw damage, as the water content in all the wall assemblies were reduced to levels far below all three critical levels of saturation. However, a small increase in the water content still occur due to the interior insulation, resulting in a slightly higher water content for the modified assemblies in comparison to the reference case (model A). As it was seen with the uncoated North and South orientations, the vapour tight assemblies (models B, C, D, E, and M) experience a slightly higher increase in the water content, in comparison to the capillary active assemblies, with the exception of the assemblies with the smart vapour retarder and the insulating plaster were the values were closer to those of the capillary active assemblies (models N, O and S). As for the capillary active assemblies, the IQ-Therm assembly, the two AAC assemblies and the two wood fibre assemblies (models J, K, L, P and Q), showed the highest water content of all the ten capillary active assemblies which were included in this study.

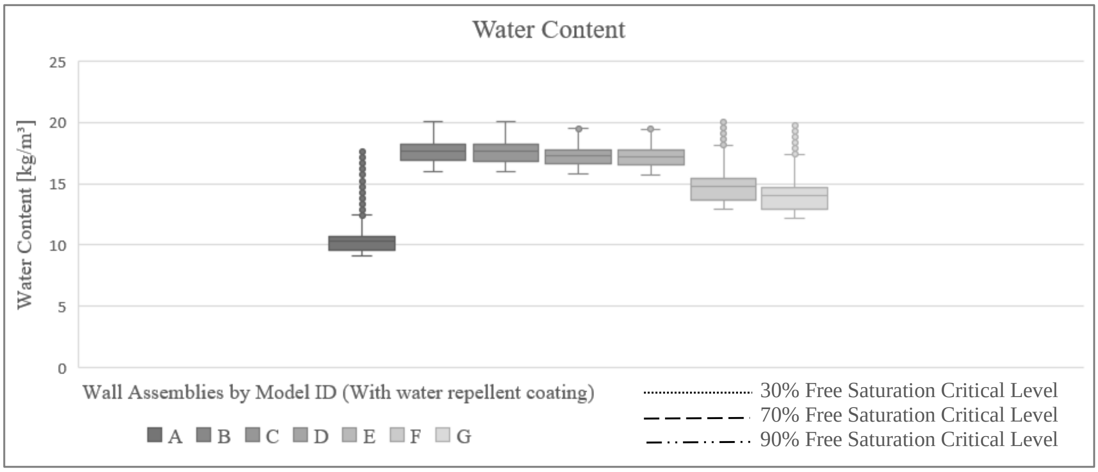


Figure 54: Water content in the wall assemblies, models A-G (South orientation with coating)

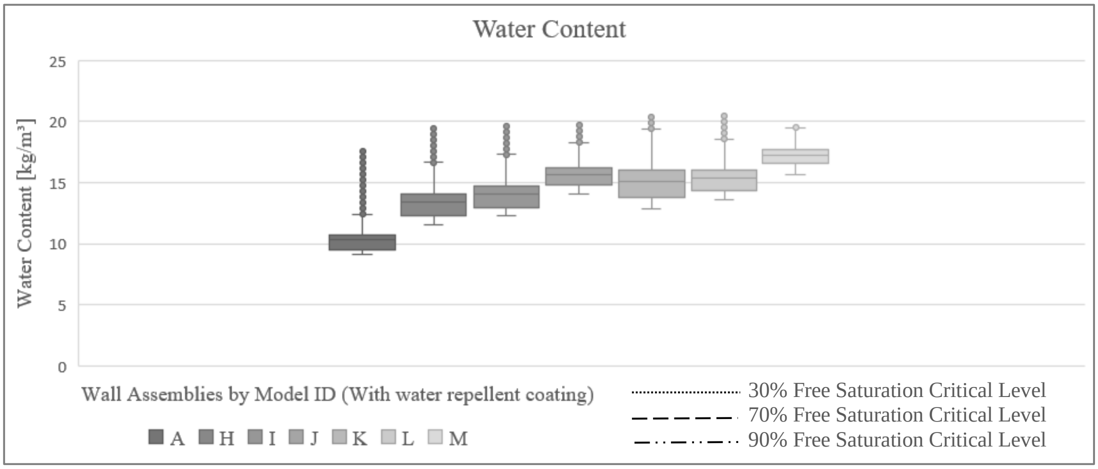


Figure 55: Water content in the wall assemblies, models A, H-M (South orientation with coating)

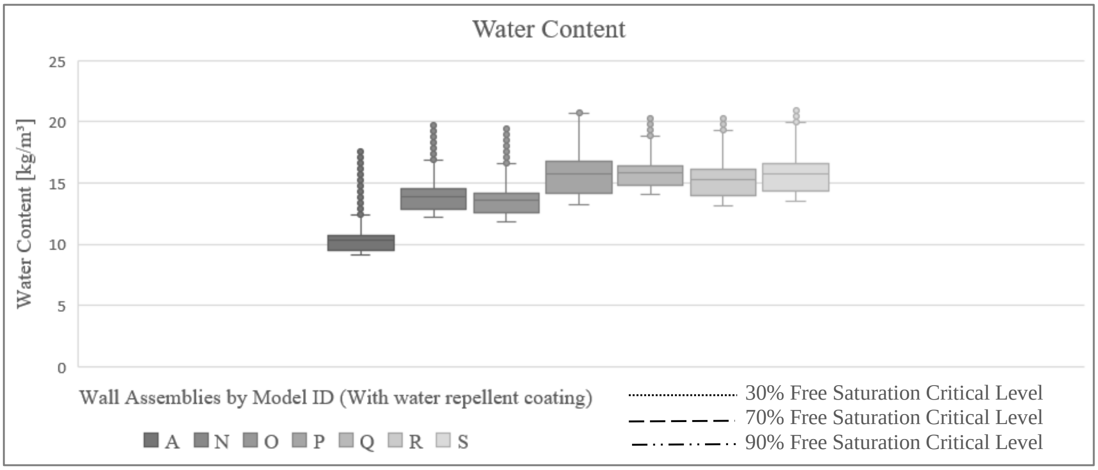


Figure 56: Water content in the wall assemblies, models A, N-S (South orientation with coating)

As it was seen with the uncoated wall assemblies, both North and South facing, the coated wall assemblies also experienced a slight drop in temperature, due to the interior insulation. In addition to experiences the slight drop in temperature, the coated wall assemblies also showed the similar trend with regard to the temperature at the first monitor location. Where no single assembly would stand out from the others, as shown in Figure 57-59.

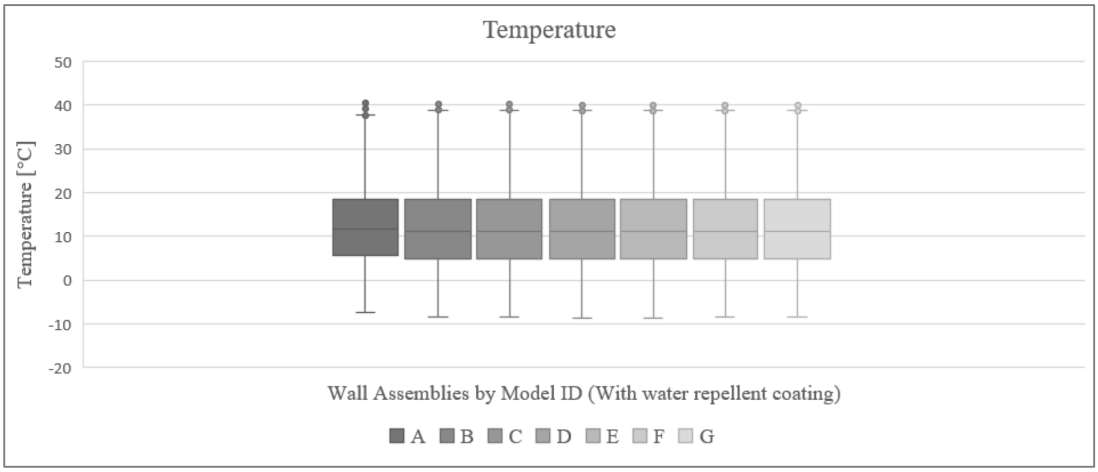


Figure 57: Temperature in the wall assemblies, models A-G (South orientation with coating)

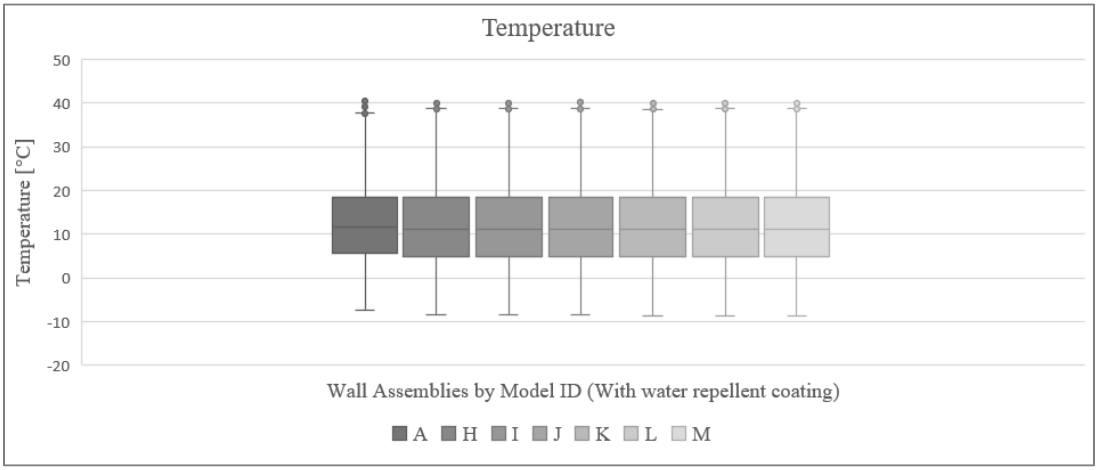


Figure 58: Temperature in the wall assemblies, models A, H-M (South orientation with coating)

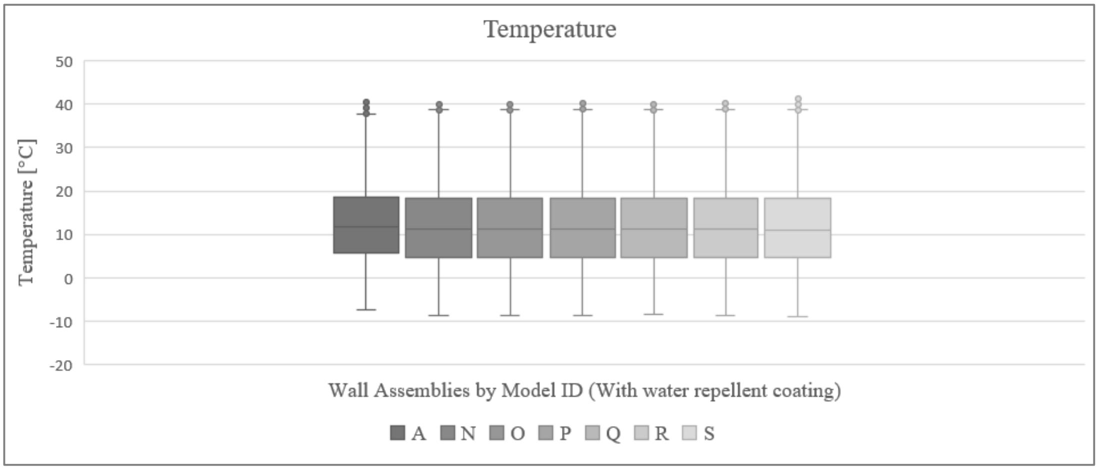


Figure 59: Temperature in the wall assemblies, models A, N-S (South orientation with coating)

In comparison to the uncoated wall assemblies with the South orientation, the coated wall assemblies actually experience a slight increase in the average temperature, as a result of the water repellent coating, as shown in Table 12. Table 12 also shows how the water repellent coating maintain a water content far below even the lower critical level of saturation of 57 kg/m^3.

Table 12: Average and standard deviation for the water content and temperature

	Water Content [kg/m3]		Temperature [°C]	
Model ID	Average	Standard deviation	Average	Standard deviation
A	10	1	12.9	8.7
B	18	1	12.3	9.0
C	18	1	12.3	9.0
D	17	1	12.3	9.0
E	17	1	12.3	9.0
F	15	1	12.3	9.0
G	14	1	12.4	9.0
H	13	1	12.4	9.0
I	14	1	12.4	9.0
J	16	1	12.3	9.0
K	15	1	12.3	9.0
L	15	1	12.3	9.0
M	17	1	12.3	9.0
N	14	1	12.3	9.0
O	14	1	12.3	9.0
P	16	2	12.3	9.0
Q	16	1	12.3	9.0
R	15	1	12.3	9.0
S	16	1	12.3	9.1

6.1.2 Wall assemblies: mould growth

As mentioned earlier, the risk of mould growth was determined by assessing the fluctuations of the temperature and relative humidity at the second monitor position, located at the interface between the existing brick wall and the new interior insulation setup. The critical level of relative humidity assessed for the risk of mould growth was 75%.

6.1.2.1 North orientation

Figure 60-62 show, that as result of the interior insulation, all the uncoated North facing wall assemblies will experience an increase in the relative humidity at the interface between the existing wall construction and the new interior insulation, in comparison to the reference case (model A). The increase due to the interior insulation, brings all the wall assemblies above the 75 % relative humidity threshold for the major part of the 30-year period. In the same way as with the water content measured at the first monitor, the vapour tight assemblies in general experience higher levels of relative humidity (models B, C, D, E, and M) in comparison to the capillary active assemblies, while the assemblies with the smart vapour retarder as well as the insulating plaster (models N, O and S) show similar results to that of the capillary active assemblies. In addition to the vapour tight assemblies, also the capillary active IQ-Therm assembly and the wood fibre assemblies (models J, P, and Q) show high levels of relative humidity. The vapour tight assemblies and the IQ-Therm assembly (Models B, C, D, E, and J) all show levels above 90% relative humidity for more than 50% of the time.

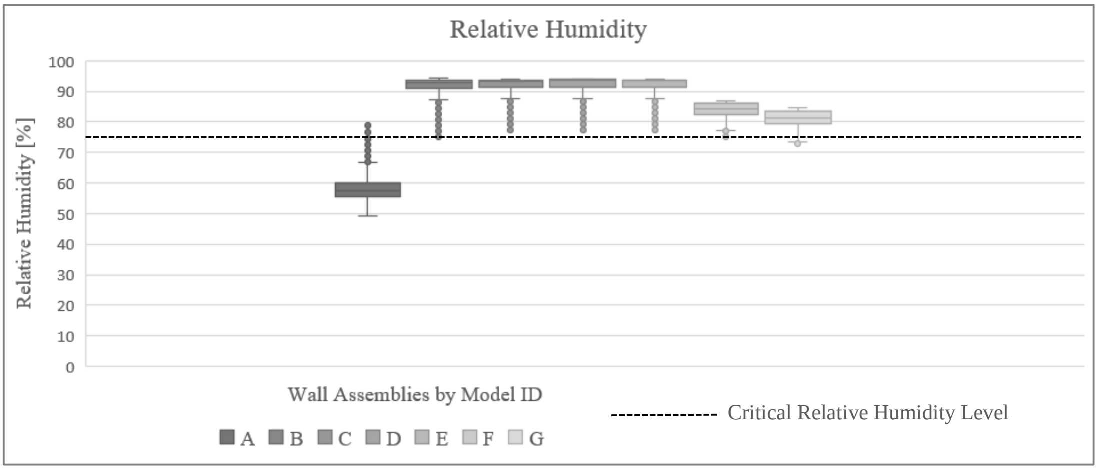


Figure 60: Relative humidity in the wall assemblies, models A-G (North orientation)

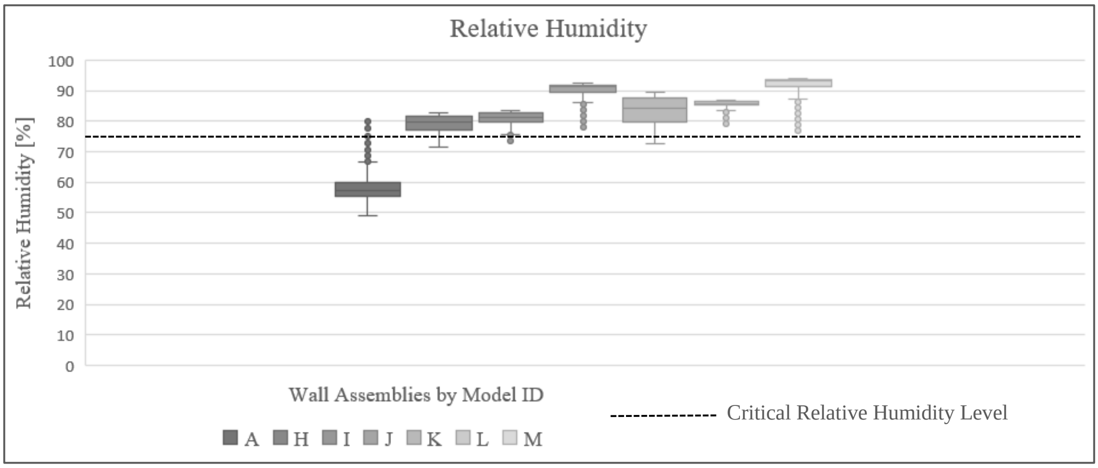


Figure 61: Relative humidity in the wall assemblies, models A, H-M (North orientation)

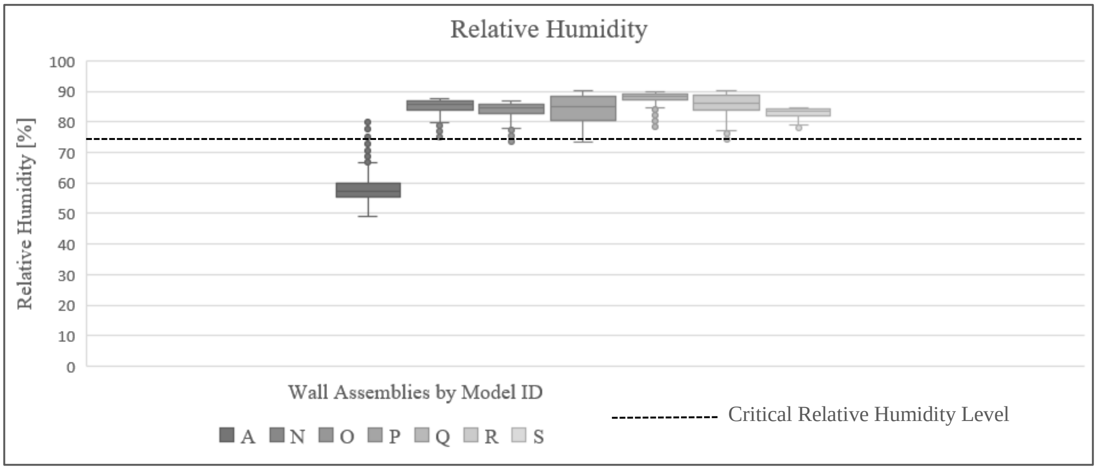


Figure 62: Relative humidity in the wall assemblies, models A, N-S (North orientation)

In contrast to the temperatures at the first monitor, where the interior insulation only caused a slight drop, the temperatures at the second monitor showed a more prominent drop as shown in Figure 63-65. But in the same way as with the temperatures at the first monitor, the temperatures at the second monitor show a similar trend between the all the wall assemblies, where no single assembly differ from the others.

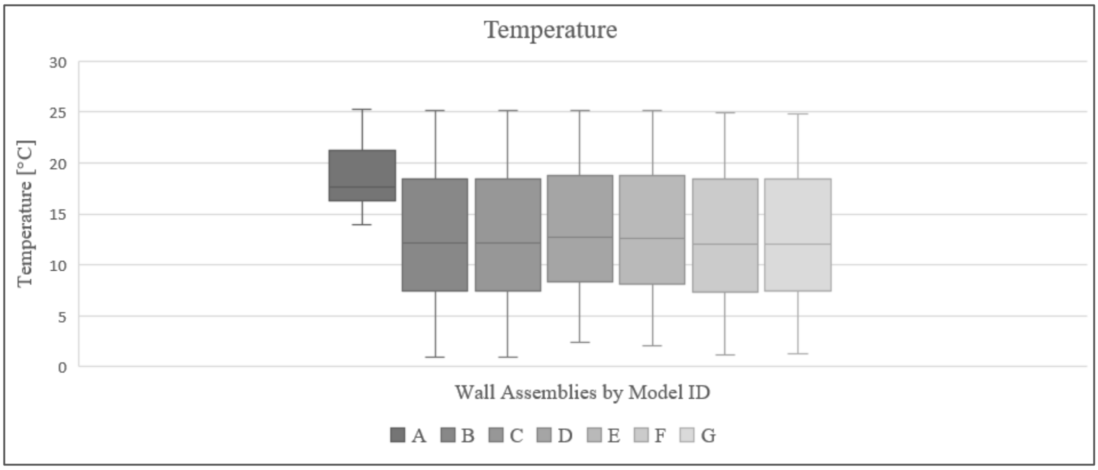


Figure 63: Temperature in the wall assemblies, models A-G (North orientation)

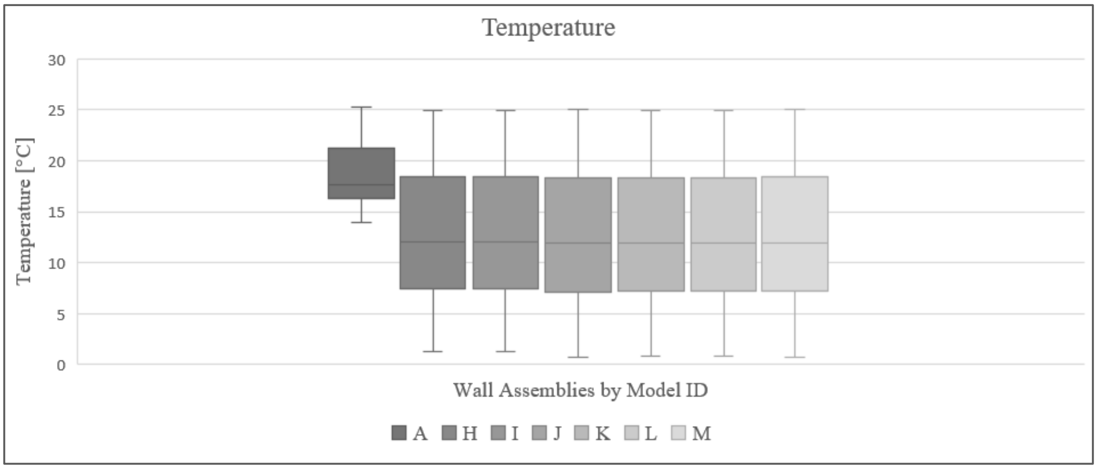


Figure 64: Temperature in the wall assemblies, models A, H-M (North orientation)

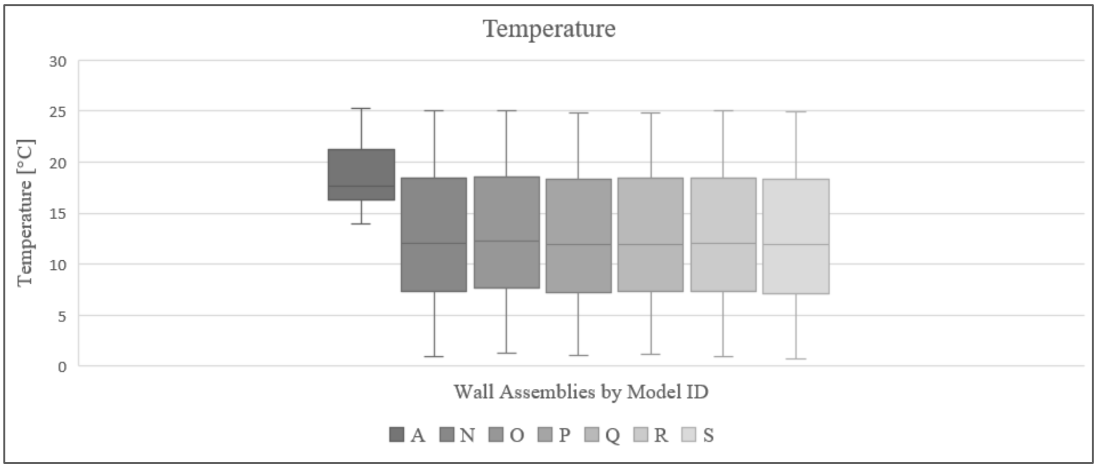


Figure 65: Temperature in the wall assemblies, models A, N-S (North orientation)

As shown in Table 13, the average relative humidity for all of the interior insulation assemblies, with the exception of the uninsulated wall, range from 79 to 92 %, simultaneously with an average temperature of 12-13 °C.

Table 13: Average and standard deviation for the relative humidity and temperature

	Relative Humidity [%]		Temperature [°C]	
Model ID	Average	Standard deviation	Average	Standard deviation
A	58	3	18.6	2.8
B	91	4	12.8	5.9
C	91	4	12.8	5.9
D	92	4	13.4	5.6
E	91	4	13.2	5.7
F	84	2	12.7	5.9
G	81	2	12.7	5.9
H	79	2	12.7	5.9
I	81	2	12.7	5.9
J	90	3	12.6	6.0
K	84	4	12.6	6.0
L	86	1	12.6	6.0
M	91	4	12.6	6.0
N	85	2	12.6	6.0
O	84	2	12.9	5.8
P	85	4	12.6	5.9
Q	88	3	12.6	5.9
R	86	3	12.7	5.9
S	83	1	12.5	6.0

Further assessment regarding the risk of mould growth in the wall assemblies were carried out though the use of Folos 2D visual mould chart, to calculate the percentage of time where the preconditions for mould growth are met for each assembly, as mentioned in section 5.5.6.3. The results are shown in Table 14 below. The results for the uncoated North facing wall assemblies showed, that three out of four Calcium Silicate assemblies as well as the assemblies with the smart vapour retarder (models G, H, I, N, and O) result in the lowest percentage of time where the preconditions for mould growth were met, ranging between 9 and 47% of the time. The YTONG South AAC assembly showed the highest percentage of time where the preconditions were met, with 70% of the time.

Table 14: Percentage of time where the preconditions for mould growth are met for the uncoated North facing assemblies

Model ID	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
Percentage of time [%]	0	59	61	67	65	55	30	9	30	60	63	70	60	47	37	67	60	66	63

6.1.2.2 South orientation

In comparison with the North facing wall assemblies, the South facing wall assemblies experience an even greater increase in the levels of relative humidity, bringing all but the insulating plaster assembly (model S) above 95% relative humidity for more than 75% of the time during the 30-year period, as shown in Figure 66-68. Despite the insulating plaster assembly showing lower levels of relative humidity in comparison to the other wall assemblies, the assembly still show a great risk for both mould and rot to occur as it is above 90% for more than 75% of the time. Although the all the capillary active assemblies lie above 95% relative humidity for more than 75% just like the vapour tight assemblies, the capillary active assemblies still show slightly better results than the vapour tight assemblies.

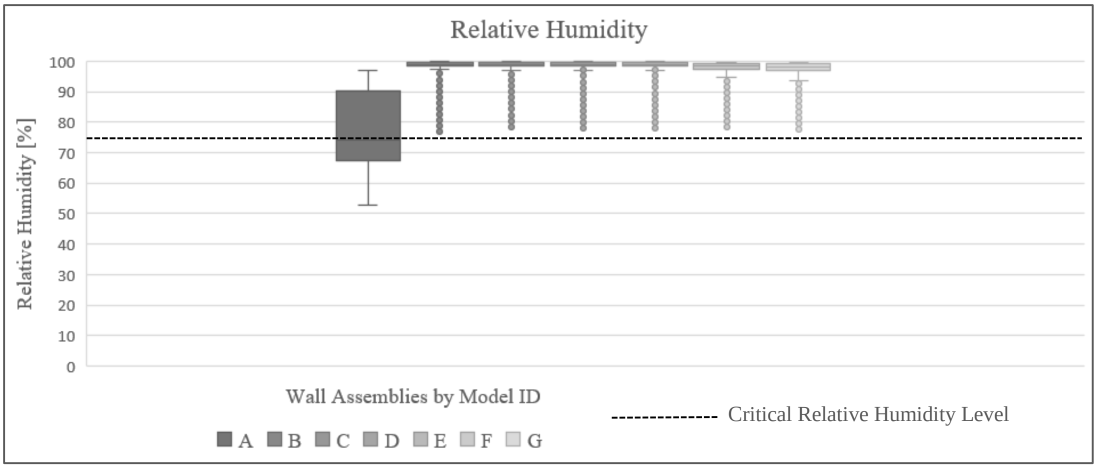


Figure 66: Relative humidity in the wall assemblies, models A-G (South orientation)

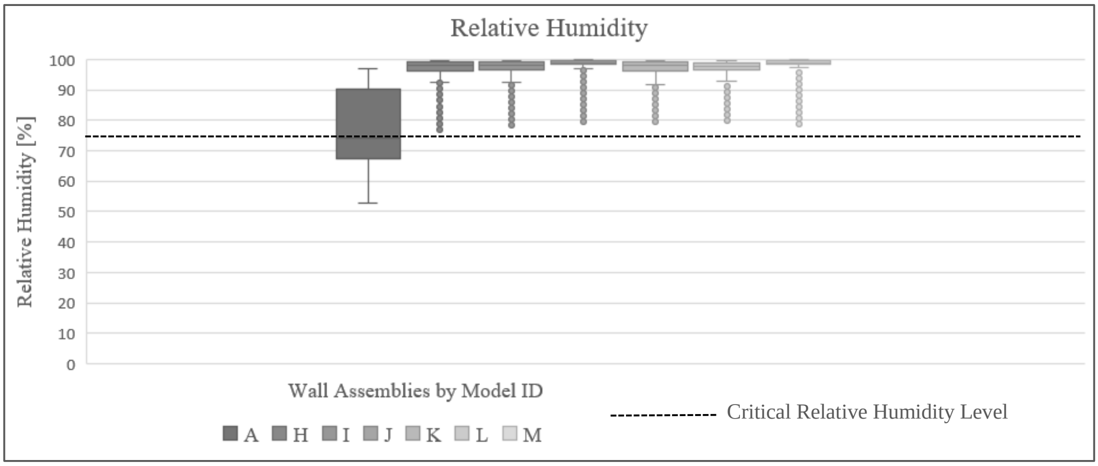


Figure 67: Relative humidity in the wall assemblies, models A, H-M (South orientation)

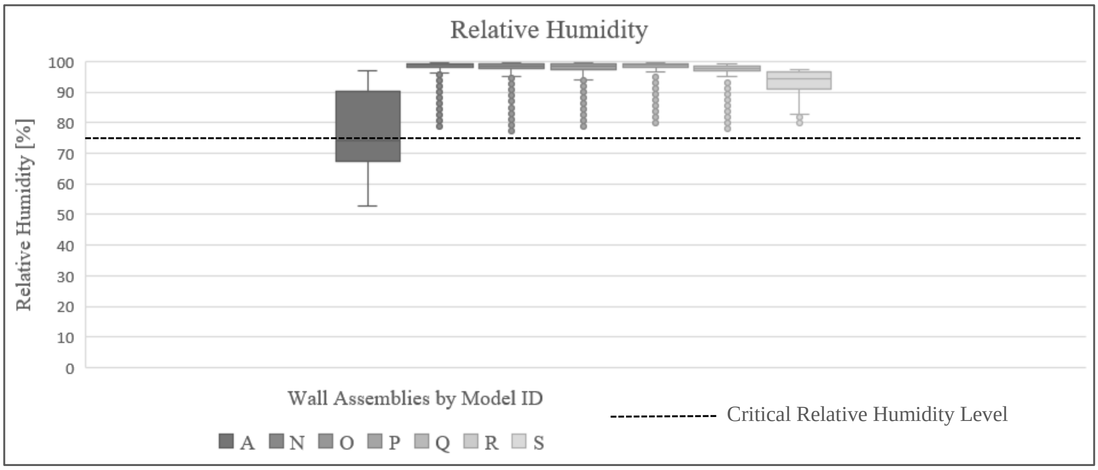


Figure 68: Relative humidity in the wall assemblies, models A, N-S (South orientation)

In the same way as with the North facing wall assemblies, the South facing wall assemblies experience a more prominent temperature drop at the interface between the existing wall and the interior insulation. And the assemblies follow a similar trend regarding the drop in temperature, as shown in Figure 69-71.

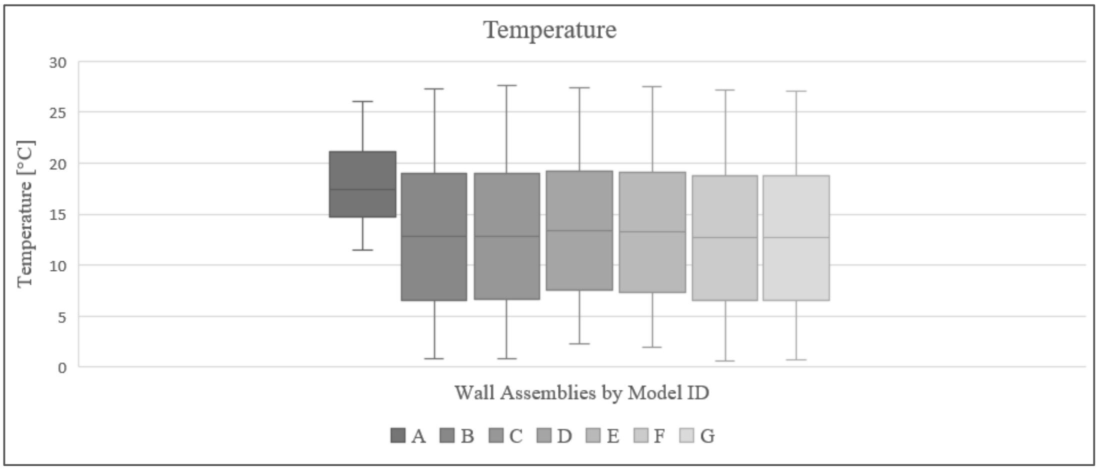


Figure 69: Temperature in the wall assemblies, models A-G (South orientation)

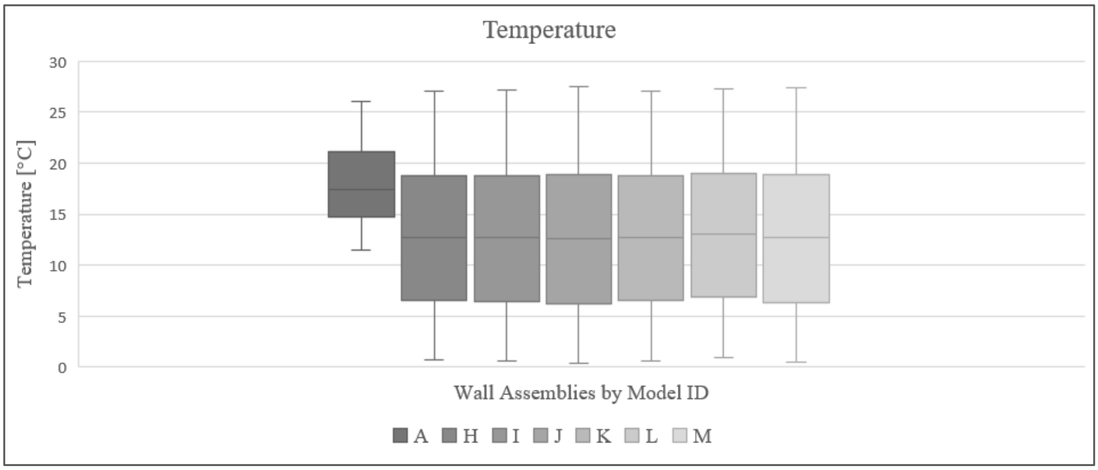


Figure 70: Temperature in the wall assemblies, models A, H-M (South orientation)

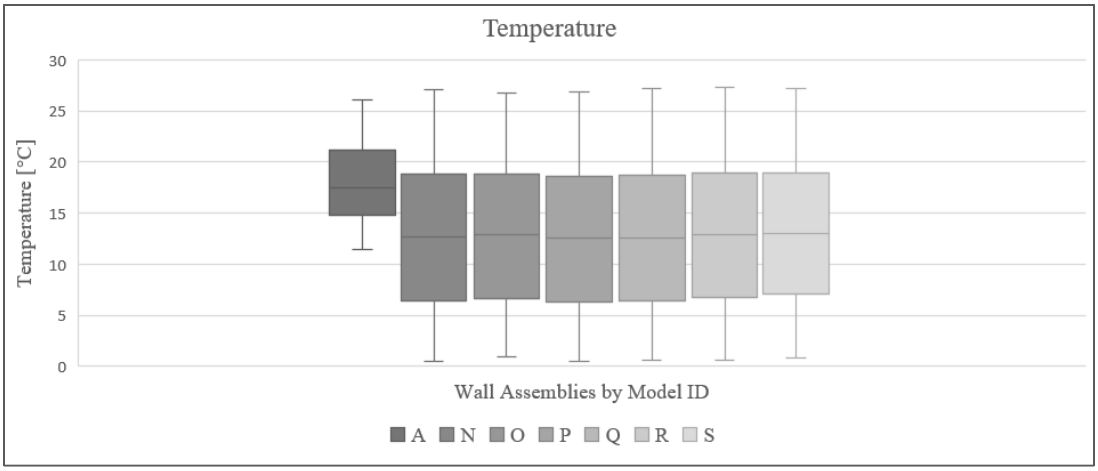


Figure 71: Temperature in the wall assemblies, models A, N-S (South orientation)

As shown in Table 15, the average relative humidity for the South facing assemblies range from 77 to 99 %, simultaneously with an average temperature of 13-14 °C. And as it was seen with the North facing assemblies, also the South facing assemblies show great risk of mould growth if not rot.

Table 15: Average and standard deviation for the relative humidity and temperature

	Relative Humidity [%]		Temperature [°C]	
Model ID	Average	Standard deviation	Average	Standard deviation
A	77	12	18.0	3.6
B	99	2	13.2	7.0
C	99	2	13.2	7.0
D	99	2	13.8	6.6
E	99	2	13.6	6.7
F	98	2	13.0	6.9
G	98	2	13.0	6.9
H	98	2	13.0	6.9
I	98	2	13.0	7.0
J	99	2	13.0	7.1
K	97	2	13.0	6.9
L	98	2	13.3	6.8
M	99	2	13.1	7.1
N	98	2	13.0	7.0
O	98	2	13.1	6.8
P	98	2	12.9	6.9
Q	99	2	13.0	7.0
R	98	2	13.2	6.9
S	94	3	13.3	6.8

In the same way as with the North facing wall assemblies, the percentage of time where the preconditions are met was also calculated for the South facing wall assemblies. The results are shown in Table 16 below. The results showed that besides the existing wall assembly, no other assembly would stay below 90% of the time where the preconditions for mould growth are met. And as it was seen with the North facing wall assemblies, the Calcium Silicate assemblies as well as the assemblies with the smart vapour retarder showed slightly lower results than the vapour tight assemblies. The results also showed that like for the North facing wall assemblies, the YTONG South AAC show the highest percentage of time where the preconditions are met.

Table 16: Percentage of time where the preconditions for mould growth are met for the uncoated South facing assemblies

Model ID	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
Percentage of time [%]	37	93	93	93	93	92	92	92	92	92	95	96	93	92	92	94	93	93	93

6.1.2.3 South orientation with water repellent coating

In comparison with uncoated North- and South facing wall assemblies, the coated South facing wall assemblies show a smaller increase in the moisture accumulation, keeping all assemblies at levels around 65-80 % relative humidity for the major part of the 30-year period, as shown in Figure 72-74. In the same way as with the uncoated wall assemblies, the vapour tight assemblies (models B, C, D, E, and M) in general experience higher levels of relative humidity than the capillary active assemblies. In contrast to the uncoated wall assemblies, with the application of the water repellent coating, the wall assemblies with the smart vapour retarder (models N and O) outperforms all other assemblies, as the relative humidity for both assemblies stay below 75% for the vast majority of the time. Most of the capillary active assemblies also show relatively good results, except for the two wood fibre assemblies (models L and K) and the two YTONG autoclaved aerated concrete assemblies (models P and Q), which ranges between 75 to 85% most of the time.

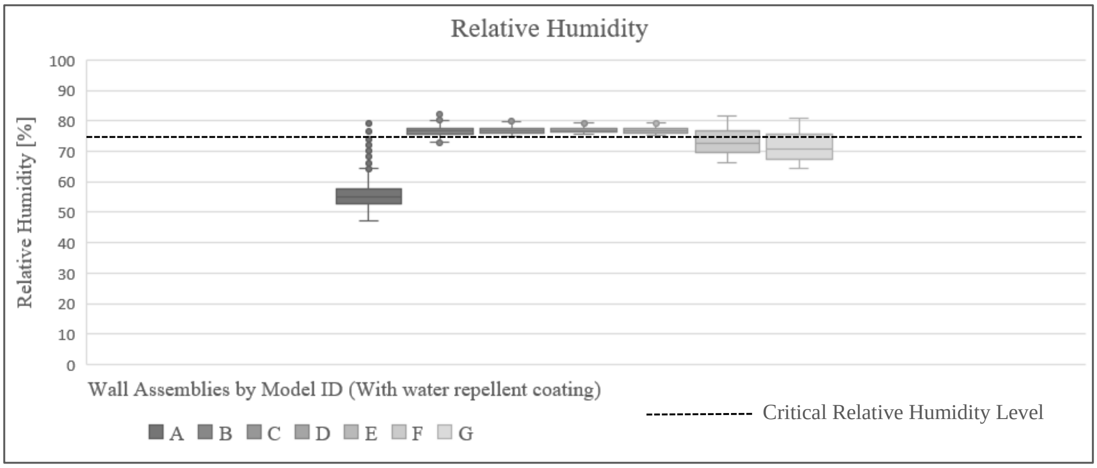


Figure 72: Relative humidity in the wall assemblies, models A-G (South orientation with coating)

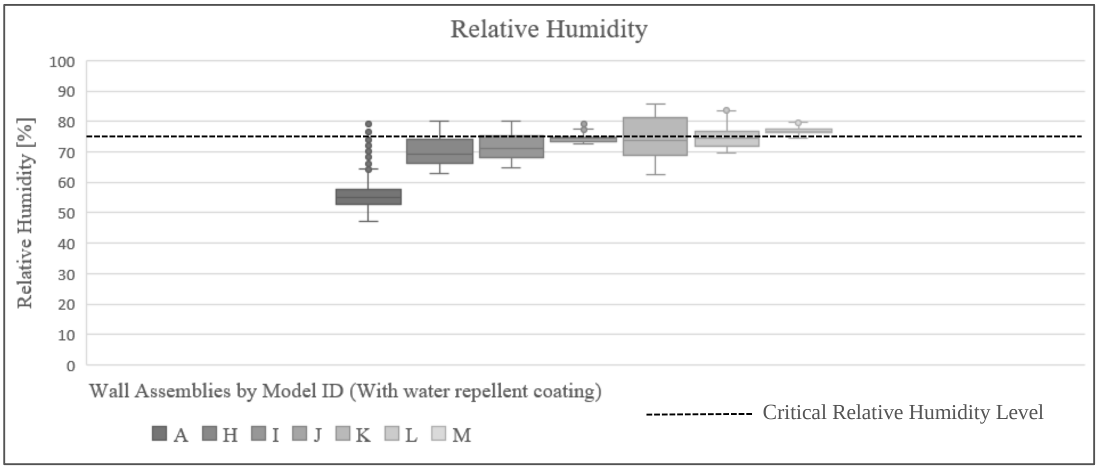


Figure 73: Relative humidity in the wall assemblies, models A, H-M (South orientation with coating)

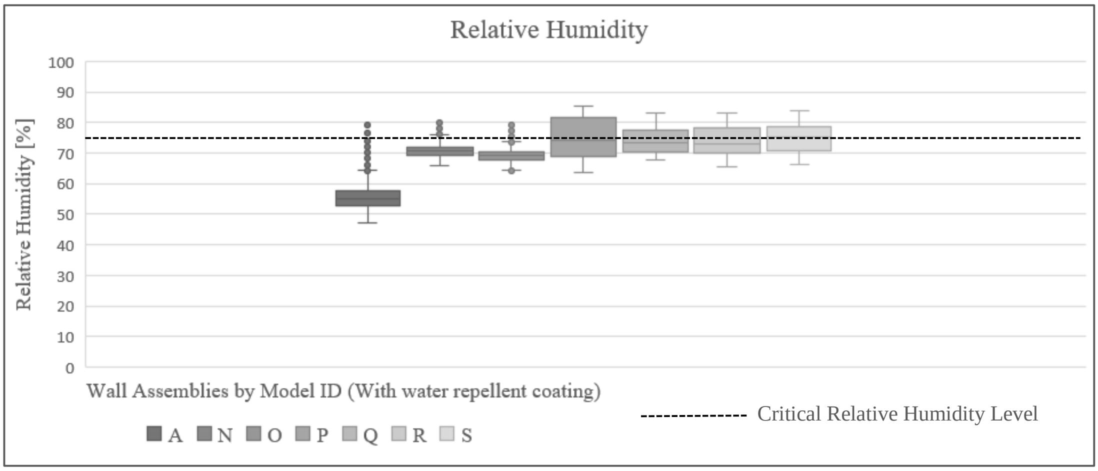


Figure 74: Relative humidity in the wall assemblies, models A, N-S (South orientation with coating)

In the same way as with both the uncoated North- and South facing wall assemblies, the coated South facing wall assemblies experience a more prominent temperature drop. Although as a result of the water repellent coating, the temperature at the interface between the existing wall and the interior insulation stay a few degrees higher than the uncoated wall assemblies. And as seen with the uncoated wall assemblies, all the coated assemblies also follow the same trend with regard to the drop in temperature, as shown in Figure 75-77.

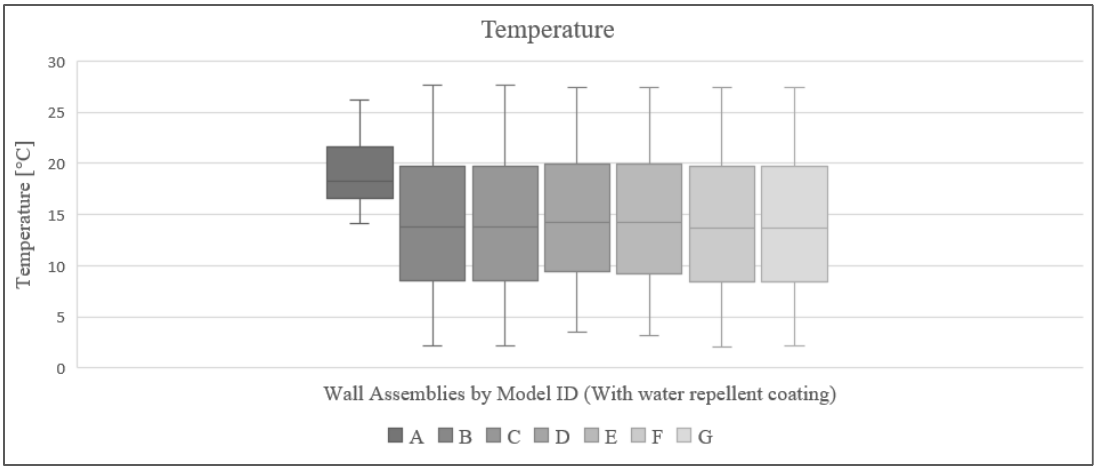


Figure 75: Temperature in the wall assemblies, models A-G (South orientation with coating)

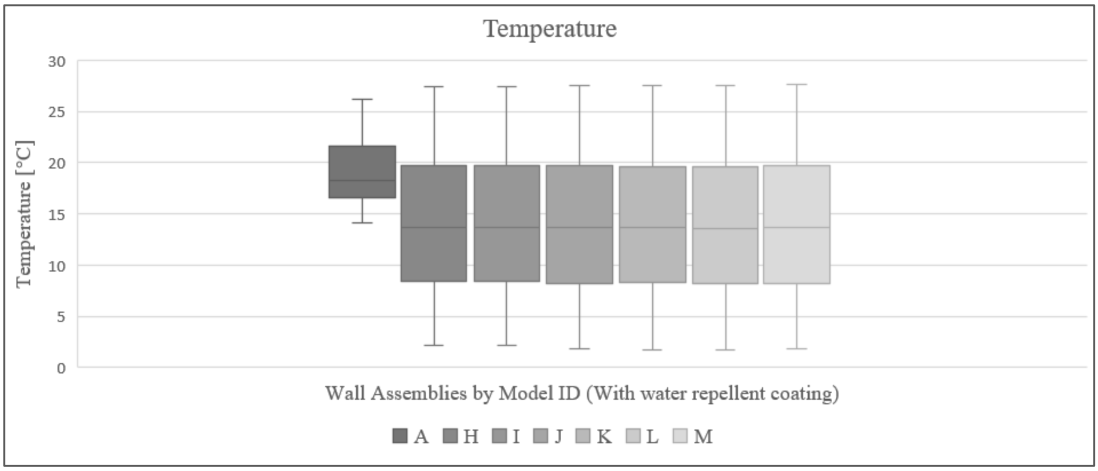


Figure 76: Temperature in the wall assemblies, models A, H-M (South orientation with coating)

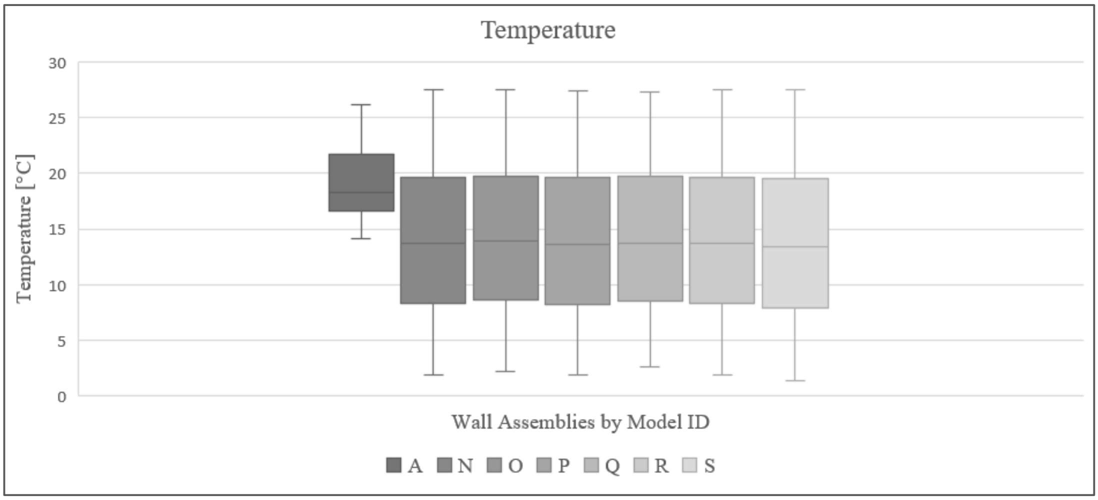


Figure 77: Temperature in the wall assemblies, models A, N-S (South orientation with coating)

As shown in Table 17, the average relative humidity for most of the capillary active wall assemblies stay below the 75 % threshold, while all the vapour tight wall assemblies (models B, C, D, E, and M) exceed this threshold, with the exception of the wall assemblies with the smart vapour retarder (models N and O). The wall assemblies with the smart vapour retarder both have an average of around 70 % relative humidity. As for the capillary active assemblies, the Calcium Silicate (models F, G, H, and I) all show values around 70-74%, while the IQ-Therm assembly, the Sto-Therm assembly, the two YTONG AAC assemblies, and the two wood fibre assemblies (models J, K, L, P, Q, and R) all show values around 74-75% relative humidity.

Table 17: Average and standard deviation for the relative humidity and temperature

	Relative Humidity [%]		Temperature [°C]	
Model ID	Average	Standard deviation	Average	Standard deviation
A	55	3	19.1	2.9
B	77	1	14.3	6.4
C	77	1	14.3	6.3
D	77	1	14.8	6.0
E	77	1	14.7	6.1
F	73	4	14.3	6.4
G	71	4	14.3	6.4
H	70	4	14.3	6.4
I	71	4	14.3	6.4
J	74	1	14.2	6.5
K	74	6	14.2	6.4
L	74	3	14.1	6.5
M	77	1	14.2	6.5
N	71	2	14.2	6.4
O	69	2	14.4	6.3
P	75	6	14.1	6.4
Q	74	4	14.4	6.3
R	74	4	14.2	6.4
S	75	4	14.0	6.6

In the same way as with the uncoated wall assemblies, the percentage of time where the preconditions are met was also calculated for the South facing wall assemblies. The results are shown in Table 18 below. The results showed that the four Calcium Silicate assemblies as well as the two assemblies with the smart vapour retarder, show the lowest risk for mould growth as the percentage of time where the preconditions for mould growth are met lies in the range of 0 to 5% during the 30-year period. Where models H and O showed the best results, with 1% and 0% of the time respectively.

Table 18: Percentage of time where the preconditions for mould growth are met for the coated South facing assemblies

Model ID	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
Percentage of time [%]	0	41	44	46	46	5	2	1	2	13	13	22	43	2	0	20	17	3	18

6.1.3 Wall assemblies: future climate scenarios

After assessing the results of the WUFI simulations for the North- and South orientations, as well as the South orientation with water repellent coating, it was determined that the four Calcium Silicate assemblies, the two SVR assemblies as well as the Sto-Therm assembly (models F, G, H, I, N, O and R), all with the water repellent coating, were the only assemblies passing both the freeze thaw- and the mould criteria. As these seven assemblies had a very low percentage of time where the preconditions for mould growth were met during the 30-year period. These seven wall assemblies were then simulated with two reference periods and four future climate scenarios as mentioned in section 5.4, and the same two monitor positions were used for determining the risk of freeze thaw damage and mould growth. Monitor position one for the risk of freeze thaw damage and monitor position two for the risk of mould growth.

6.1.3.1 Freeze thaw damage

As seen for the current climate data, the water repellent coating succeeds in keeping the water content in all the wall assemblies below the three critical levels of saturation for both the two reference periods as well as the four future climate scenarios at monitor one, see Figure 78-83. When compared to the current climate data, the results for the future climate scenarios show that there will be a slight increase in the water content. As seen in the results for the current climate data, the water content for the seven approved assemblies was generally below 15 kg/m^3 for 75% of the time. While for the CNRM future climate scenarios, the results showed that the water content in the assemblies was in the range 15-23 kg/m^3 for 75% of the time. The IPSL future climate scenarios also showed an increase in the water content compared to the current climate data, however, the change was not a big as for the CNRM future climate scenarios. Instead of 75% of the time with a water content in the range 15-23 kg/m^3, the IPSL results showed around 50% of the time above 15 kg/m^3.

Comparing the different assemblies, show that the Calcium Silicate assemblies (models F, G, H, and I) in general maintain a lower water content than the Sto-Therm assembly and the assemblies with the smart vapour retarder (models N, O, and R). As seen in for the current climate data, the Sto-Therm assembly showed the highest water content, while the Calcium Silicate Washington (model H) showed the lowest water content in all the future climate scenarios.

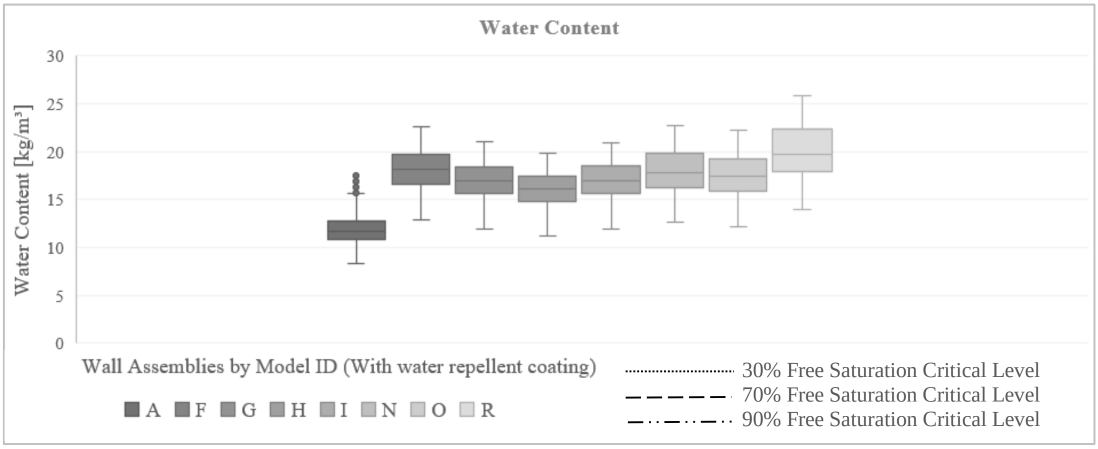


Figure 78: Water content in the wall assemblies (South orientation with coating, climate file CNRM_1961-1990)

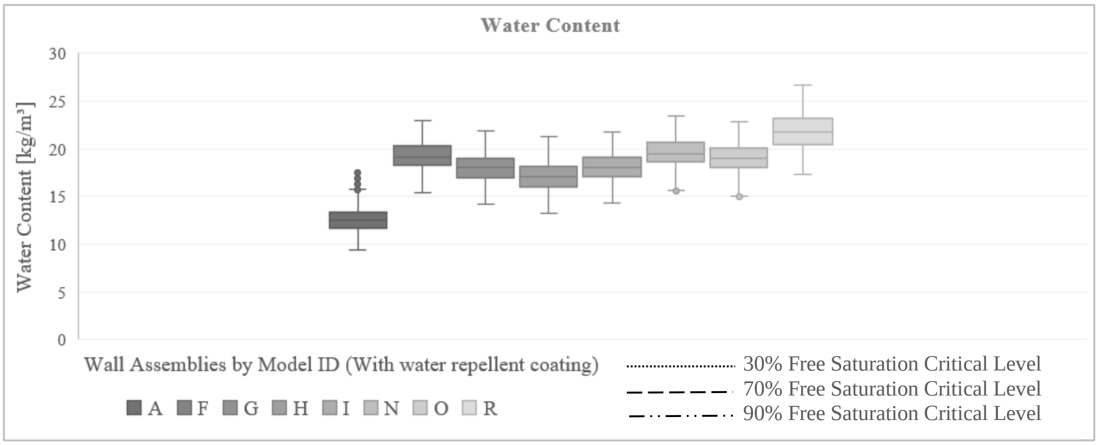


Figure 79: Water content in the wall assemblies (South orientation with coating, climate file CNRM_2021-2050)

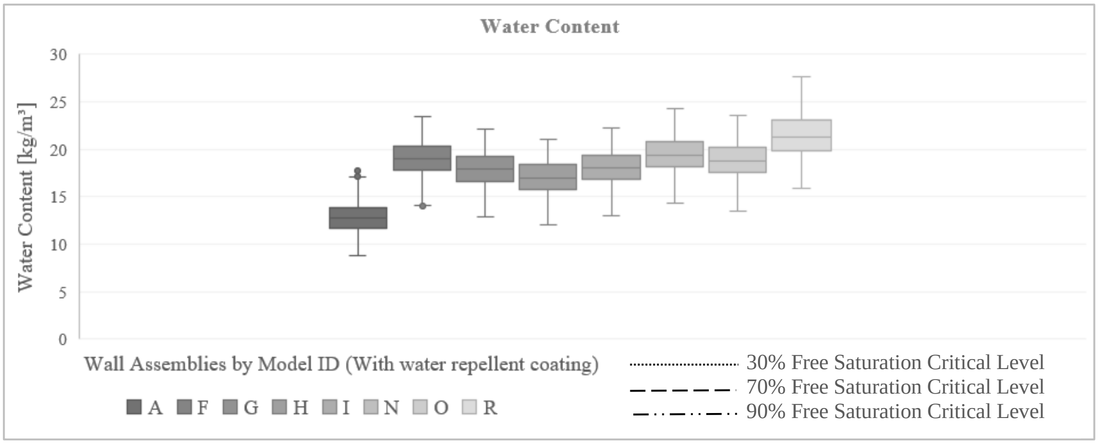


Figure 80: Water content in the wall assemblies (South orientation with coating, climate file CNRM _2071_2100)

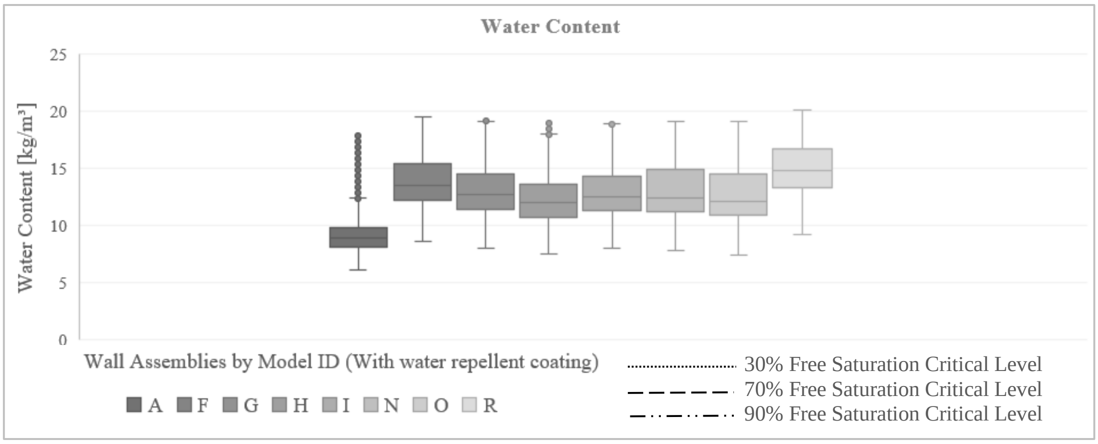


Figure 81: Water content in the wall assemblies (South orientation with coating, climate file IPSL_1961-1990)

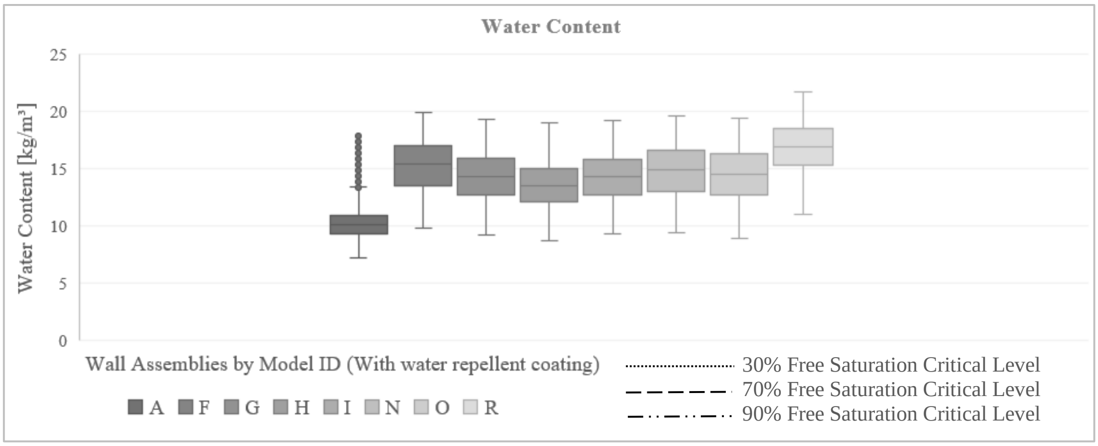


Figure 82: Water content in the wall assemblies (South orientation with coating, climate file IPSL _2021_2050)

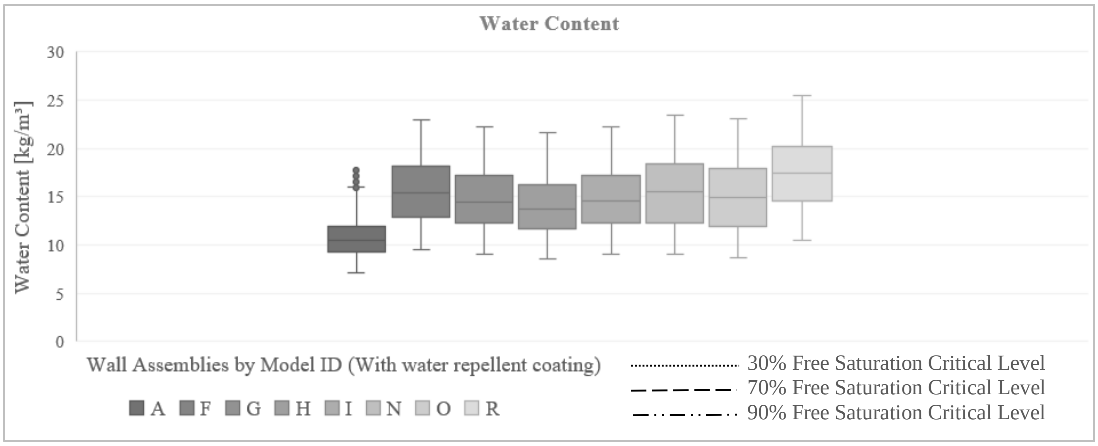


Figure 83: Water content in the wall assemblies (South orientation with coating, climate file IPSL_2071-2100)

As seen in for the current climate data, the temperature at the first monitor only experience a slight drop in temperature when the modified wall assemblies are compared to the existing wall. This temperature trend is similar for all the future climate scenarios, se Figure 84-89. When future climate scenarios, however, are compared to each other, then the results show an increase in the temperature between the three different periods, 1961-1990, 2021-2050, and 2071-2100. Comparing the CNRM results to the IPSL results, show that the temperatures in the wall assemblies with the CNRM climate scenarios are a slightly higher than the temperatures in the wall assemblies with the IPSL climate scenarios.

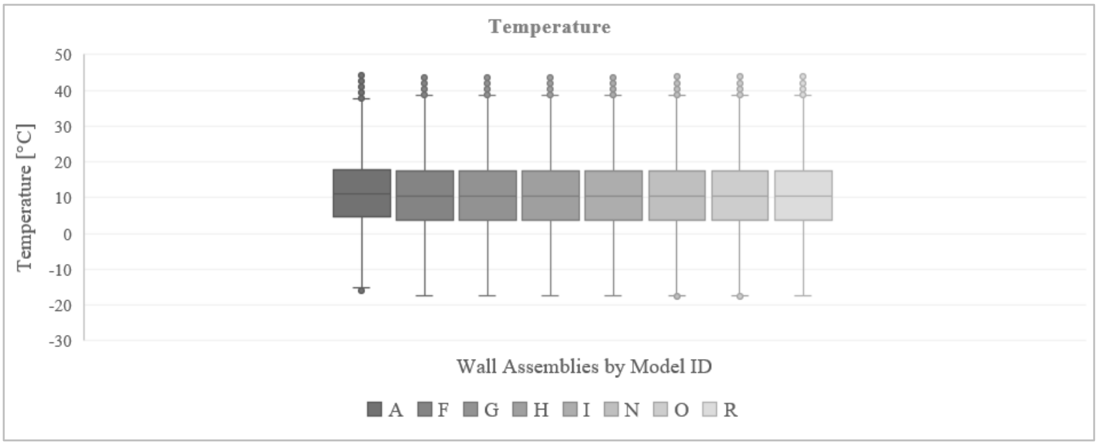


Figure 84: Temperature in the wall assemblies (South orientation with coating, climate file CNRM_1961-1990)

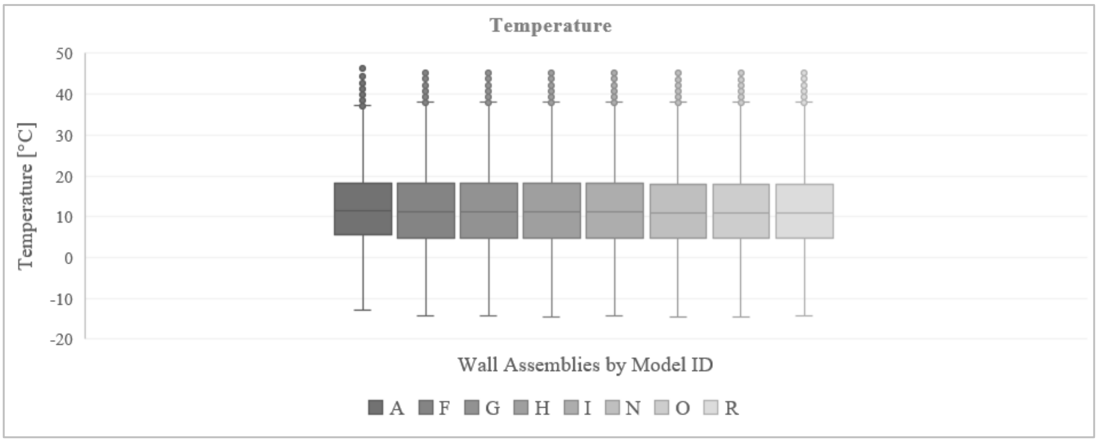


Figure 85: Temperature in the wall assemblies (South orientation with coating, climate file CNRM_2021-2050)

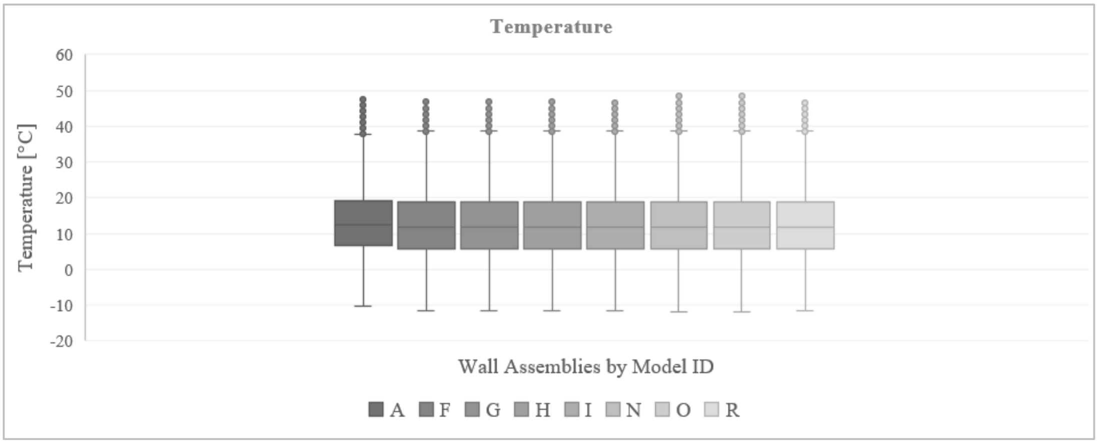


Figure 86: Temperature in the wall assemblies (South orientation with coating, climate file CNRM_2071-2100)

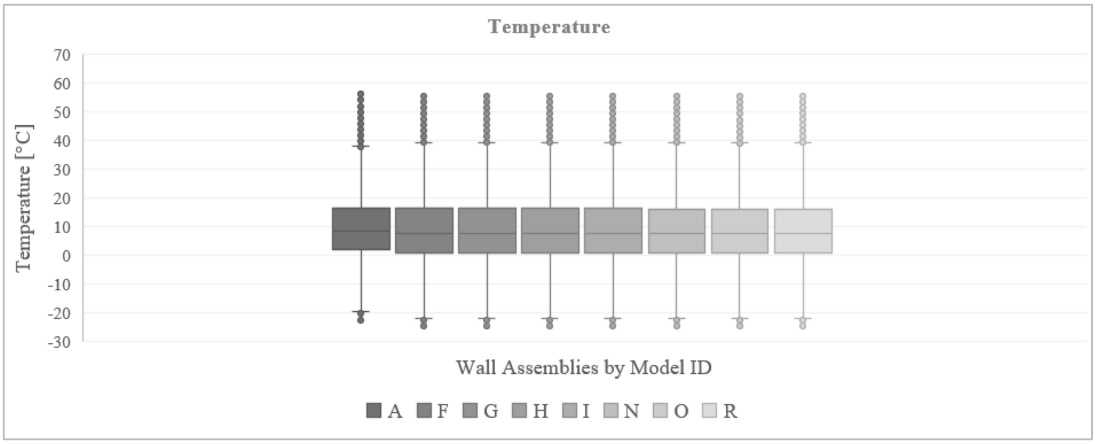


Figure 87: Temperature in the wall assemblies (South orientation with coating, climate file IPSL_1961-1990)

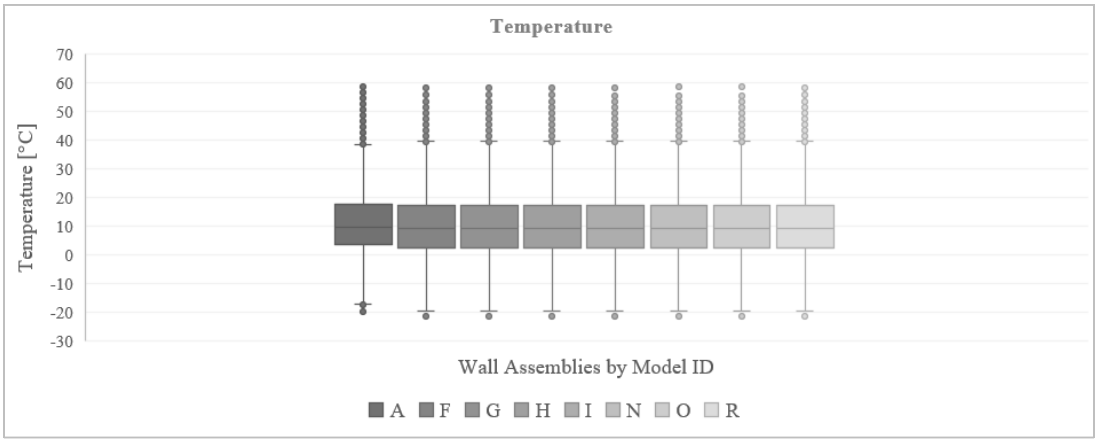


Figure 88: Temperature in the wall assemblies (South orientation with coating, climate file IPSL_2021-2050)

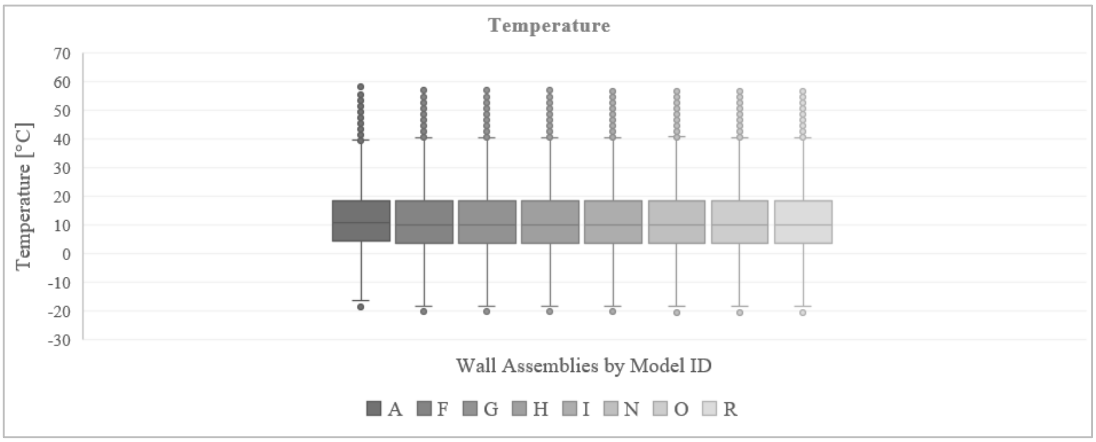


Figure 89: Temperature in the wall assemblies (South orientation with coating, climate file IPSL_2071-2100)

The results showed how the average values for the water content and temperature at monitor one generally is a bit higher for CNRM climate scenarios than for the IPSL climate scenarios, as shown in Figure 90-93, which is a common trend for all the wall assemblies. However, in contrast to the higher average water content and temperature for the CNRM results, the IPSL results in general show a higher standard deviation for both water content and temperature in comparison to the CNRM results. Although the standard deviation was shown to be higher for the IPSL results, it will still not bring any of the wall assemblies into the risk zone with regards to freeze thaw damages.

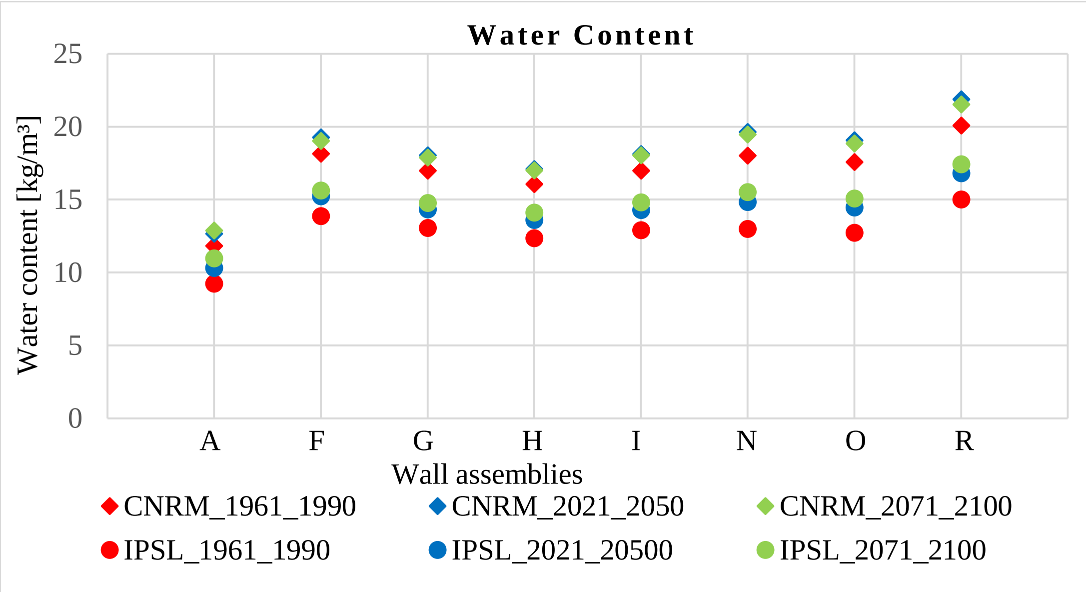


Figure 90: Average water content for the future climate scenarios

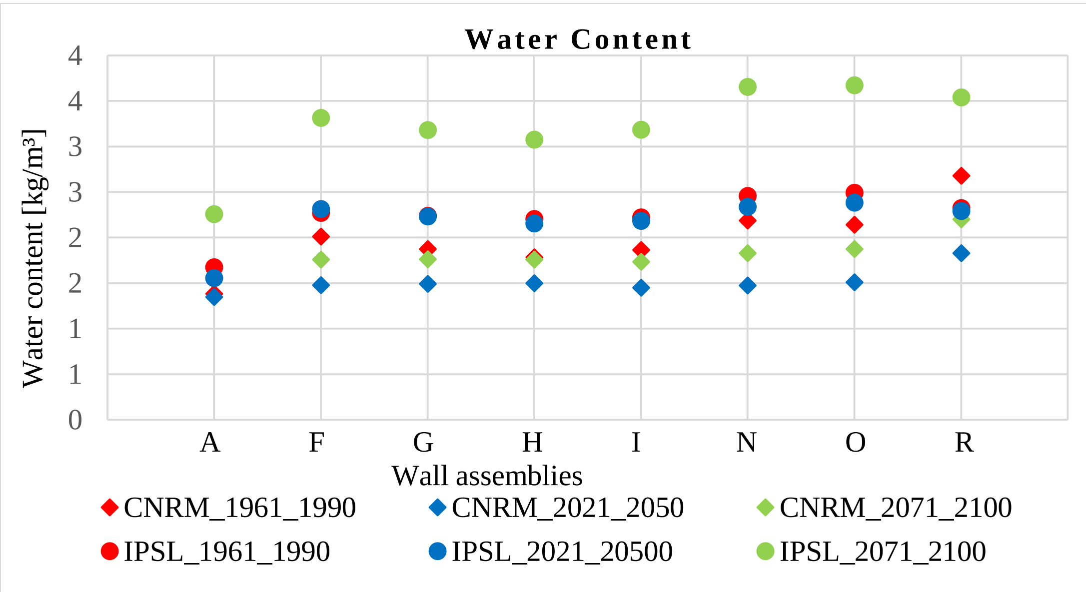


Figure 91: Standard deviation for the water content for the future climate scenarios

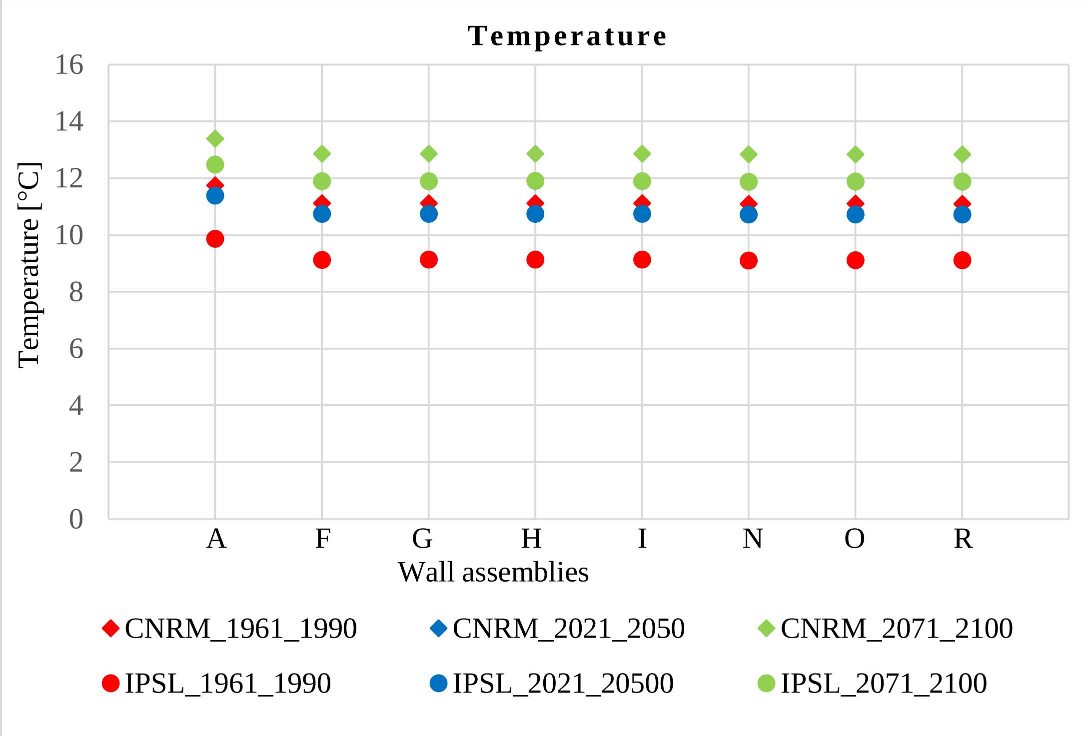


Figure 92: Average temperature for the future climate scenarios

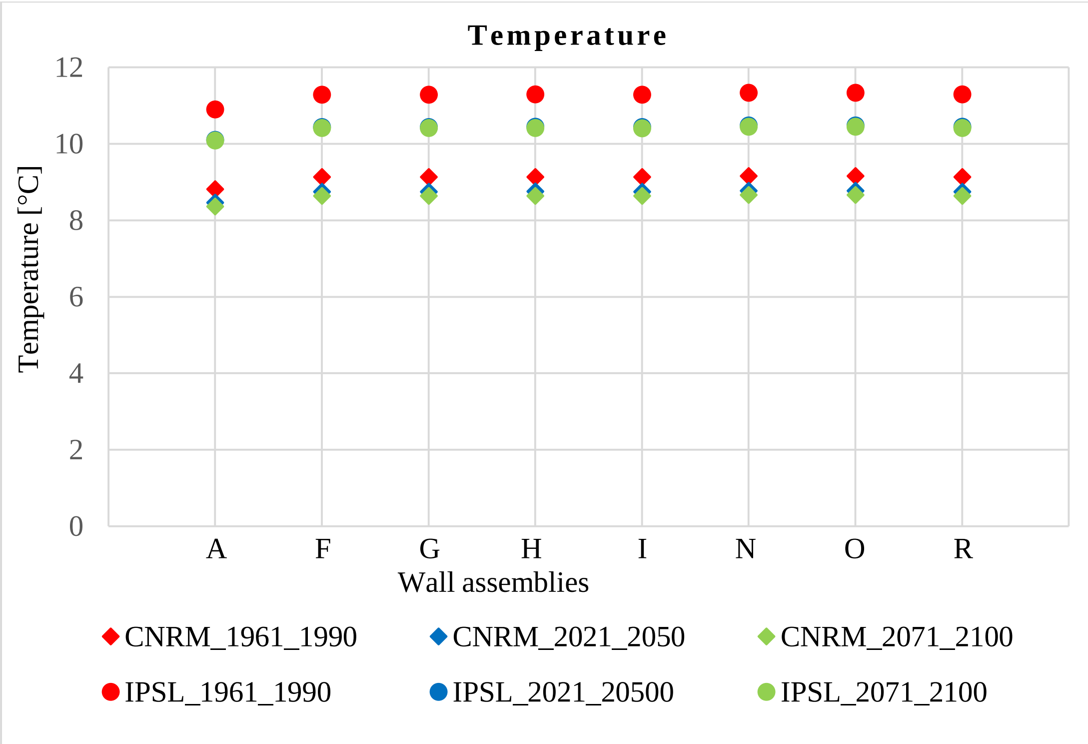


Figure 93: Standard deviation for the temperature for the future climate scenarios

6.1.3.2 Mould growth

In the same way as with the current climate data, the two wall assemblies with the smart vapour retarder (models N and O) outperforms the Calcium Silicate assemblies (models F, G, H, and I) as well as the Sto-Therm assembly (model R) with respect to maintaining a low relative humidity at monitor two, as shown in Figure 94-99 below. The relative humidity in the assemblies with the smart vapour retarder stay below the critical level of 75% for more than 75% of the time during the 30-year period, which was common for all he future climate scenarios. As for the Calcium Silicate assemblies, all four assemblies manage to stay below 75% relative humidity for approximately 50% of the time during the 30-year period. The Calcium Silicate Washington assembly (model H) was shown to perform the best of the four Calcium Silicate assemblies, maintaining a relative humidity less than 75% for almost 75% of the time in a few of the cases. The Sto-Therm assembly showed to perform worst of all the assemblies simulated with the future climate scenarios, as the assembly exceeds the 75% relative humidity threshold for almost 75% of the time.

As seen for the results from monitor one, when comparing the results of the different future climate scenarios against each other, the CNRM results tend to be slightly worse than the IPSL with respect to the relative humidity. As a result, the assemblies experience a higher percentage of time exceeding the 75% relative humidity threshold with the CNRM climate model in comparison to the IPSL climate model. Furthermore, comparing the three time periods for CNRM- and IPSL climate models, show only a very small increase or decrease for in the results for the wall assemblies. An example of this is show in Figure 94-96, where the Sto-Therm- and Calcium Silicate assemblies experience a small decrease between the time periods 1961-1990 and 2021-2050, and again between 2021-2050 and 2071-2100 with the CNRM climate model.

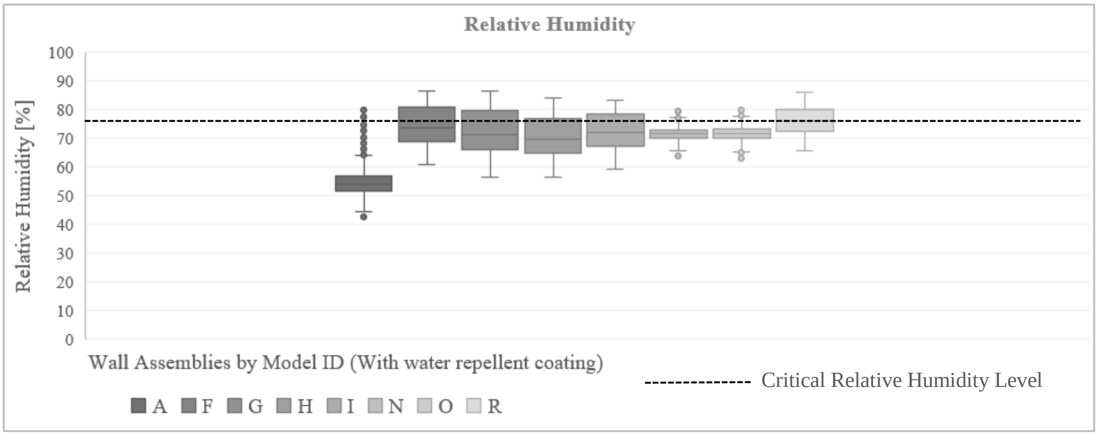


Figure 94: Relative humidity in the wall assemblies (South orientation with coating, climate file CNRM _1961_1990)

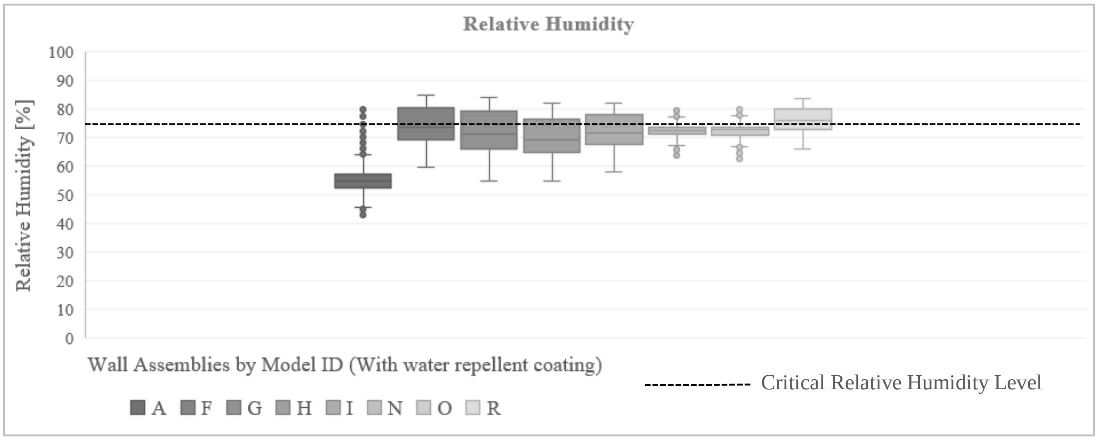


Figure 95: Relative humidity in the wall assemblies (South orientation with coating, climate file CNRM _2021_2050)

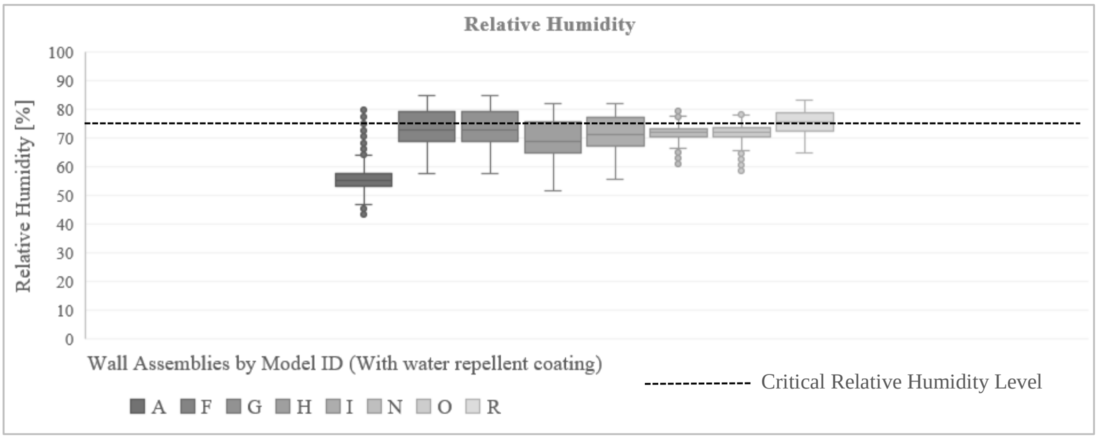


Figure 96: Relative humidity in the wall assemblies (South orientation with coating, climate file CNRM _2071_2100)

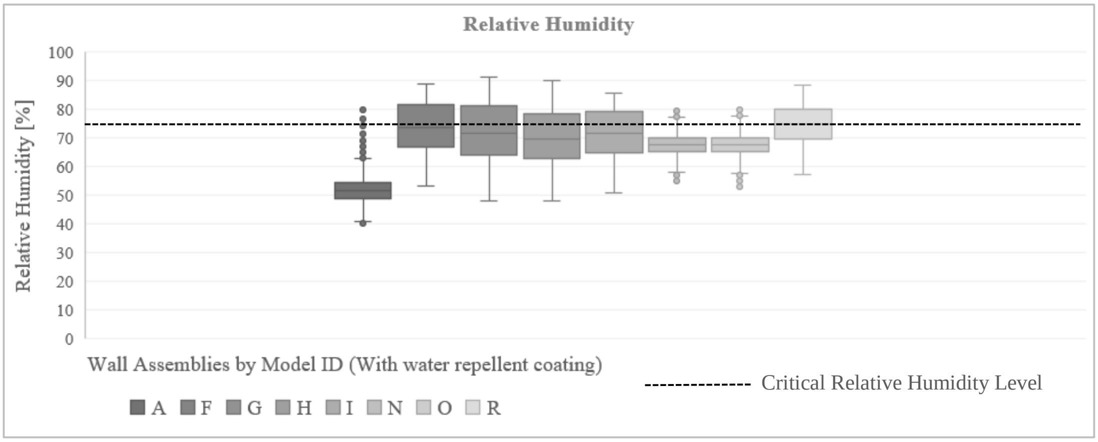


Figure 97: Relative humidity in the wall assemblies (South orientation with coating, climate file IPSL_1961_1990)

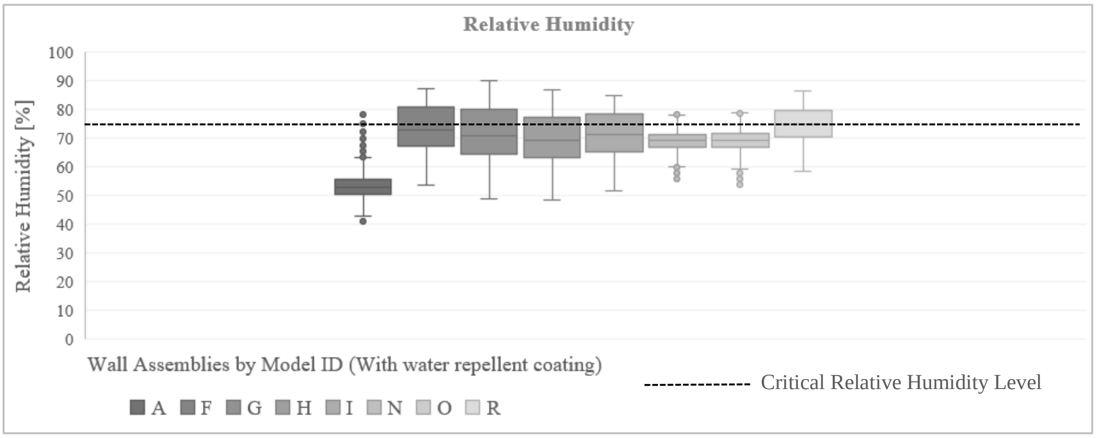


Figure 98: Relative humidity in the wall assemblies (South orientation with coating, climate file IPSL _2021_2050)

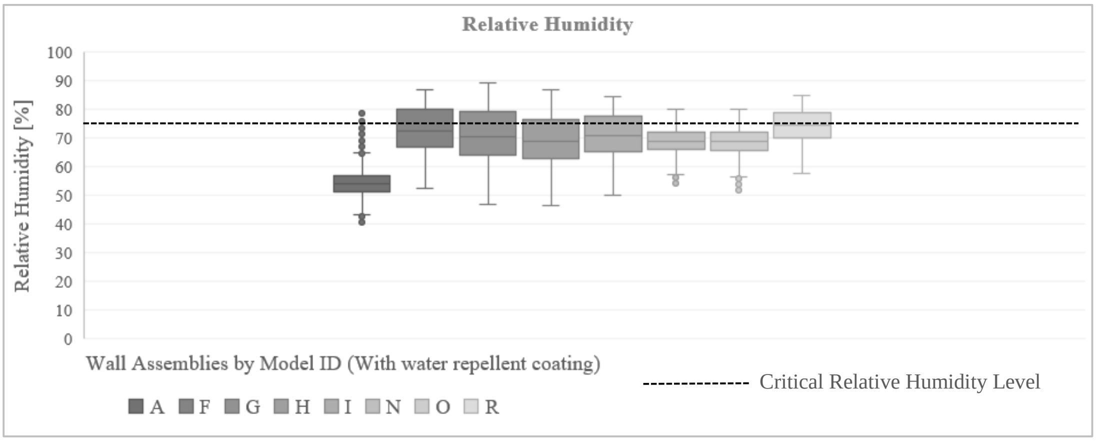


Figure 99: Relative humidity in the wall assemblies (South orientation with coating, climate file IPSL _2071_2100)

Regarding the temperatures measured at monitor two, the results showed that a small increase in temperature occurred between the different time periods for each of the climate models, as shown in Figure 100-105. The results from the CNRM climate model showed an increase in temperature of approximately 0.5 °C between 1961-1990 and 2021-2050, and 0.5-1.0 °C between 2021-2050 and 2071-2100. While the results from the IPSL climate models generally showed an increase of approximately 1.2-1.3 °C between 1961-1990 and 2021-2050, and an increase of approximately 0.9-1.0 °C between 2021-2050 and 2071-2100.

When comparing the future climate scenarios with the current climate data from Gothenburg, then the results show that the middle 50% of the temperature values do not differ greatly from the current climate data. The middle 50% in both the current and the future climate scenarios range from approximately 8 to 20 °C. In contrast to the middle 50%, both the lower and upper 25% (illustrated by the whiskers in the boxplot) showed an increase in the temperature fluctuations. As the lower 25% of the temperature values, originally ranging from 2 to 8 °C, would increase to a range of -3 to 8 °C for the CNRM climate models, and -10 to 8 °C for the IPSL. In the same way would the upper 25% of the temperature values originally ranging from 20 to 27 °C, experience and increase to a range of 20 to 30 °C for the CNRM climate models, and 20 to 32 °C for the IPSL. The increased temperature fluctuation in the lower and upper 25% of the values would suggest that the wall assemblies will experience more extreme temperature conditions in the future, both in the lower and upper part of the scale.

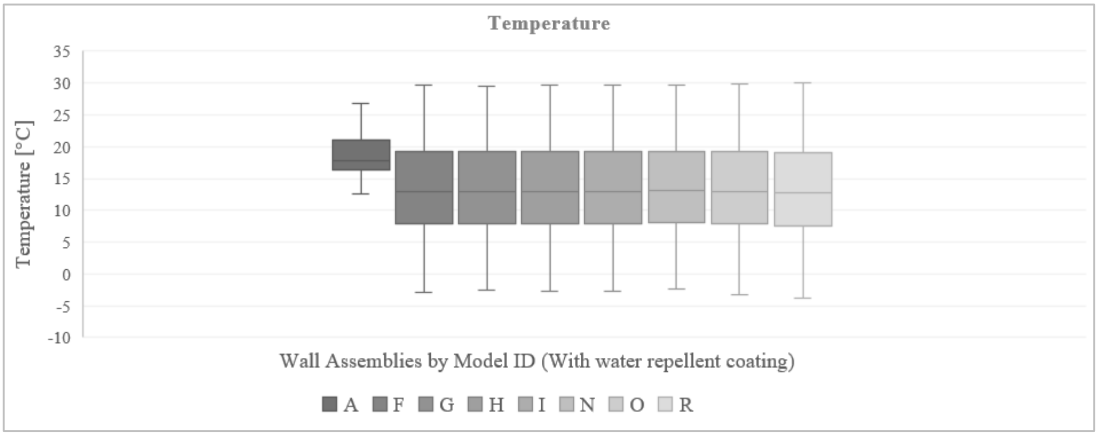


Figure 100: Temperature in the wall assemblies (South orientation with coating, climate file CNRM _1961_1990)

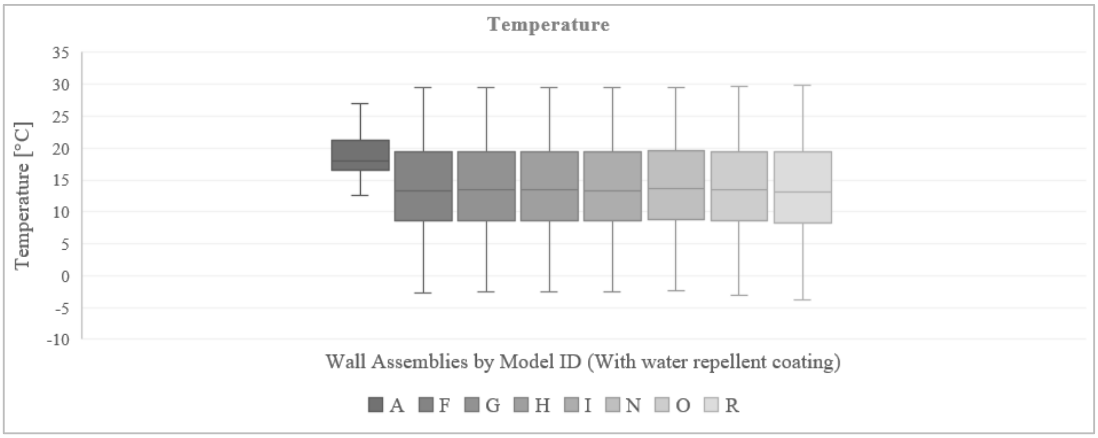


Figure 101: Temperature in the wall assemblies (South orientation with coating, climate file CNRM _2021_2050)

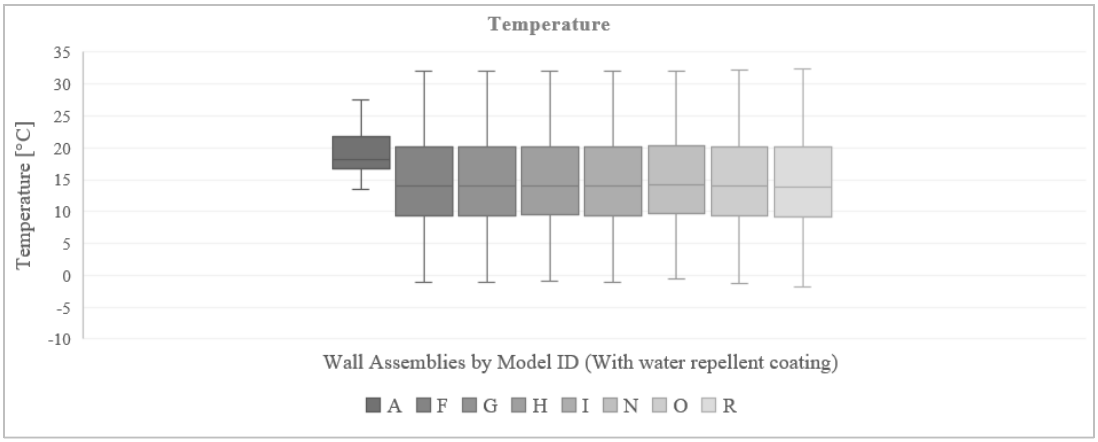


Figure 102: Temperature in the wall assemblies (South orientation with coating, climate file CNRM _2071_2100)

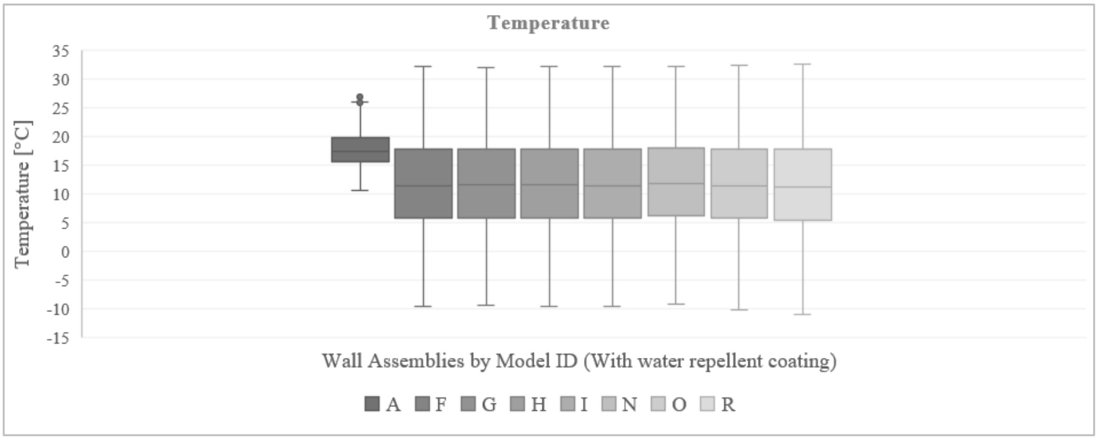


Figure 103: Temperature in the wall assemblies (South orientation with coating, climate file IPSL _1961_1990)

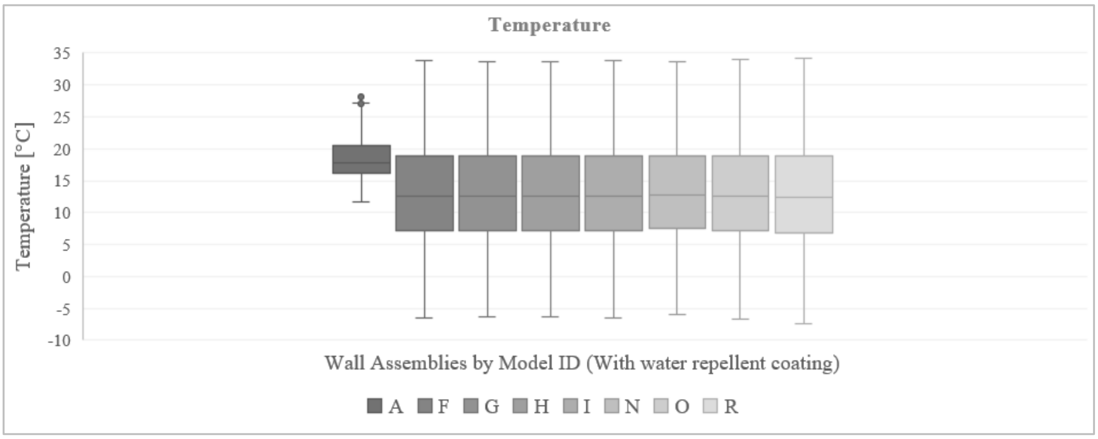


Figure 104: Temperature in the wall assemblies (South orientation with coating, climate file IPSL _2021_2050)

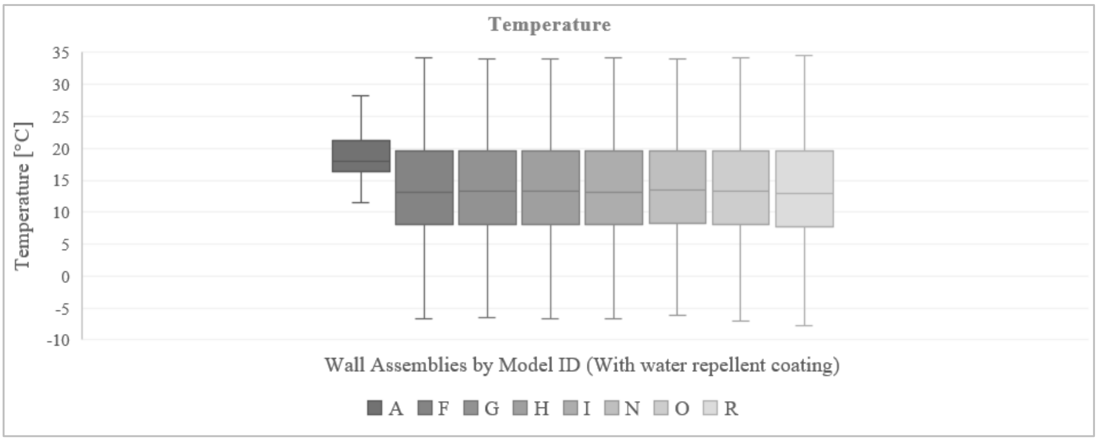


Figure 105: Temperature in the wall assemblies (South orientation with coating, climate file IPSL _2071_2100)

In the same way as with monitor one, the results showed that the average temperature and humidity values were higher for the wall assemblies simulated with the CNRM climate model than for the IPSL climate model. In addition to the higher average values with the CNRM climate model, the results also showed that the standard deviation for the temperature and humidity values were higher for the IPSL climate model, as seen for the standard deviation at monitor one. Comparison of the average values for the relative humidity between the different future climate scenarios shown in Figure 106, showed that the smart vapour retarder assemblies as well as the Calcium Silicate Washington assembly (models H, N, and O) in general performed better than the other assemblies, as these assemblies maintain a relative humidity around 69-72%. In addition to the low relative humidity in models H, N, and O, further assessment of the results showed that the smart vapour retarder assemblies would experience only a slight increase in the relative humidity during the different periods. As the standard deviation for model N and O was around 2-4%, as shown in Figure 107, which would suggest that the two smart vapour retarder assemblies would stay below the critical level of 75% relative humidity for almost the entire time.

As for the temperature values in the different assemblies, the results showed only little difference between the modified wall assemblies both in average temperature and for the standard deviation, as shown in Figure 108-109 The only real difference occurred between the CNRM results and the IPSL results, as mentioned earlier. Comparing the existing wall with the modified wall assemblies showed that the results for the future climate scenarios differed more from each other with the interior insulation than without it.

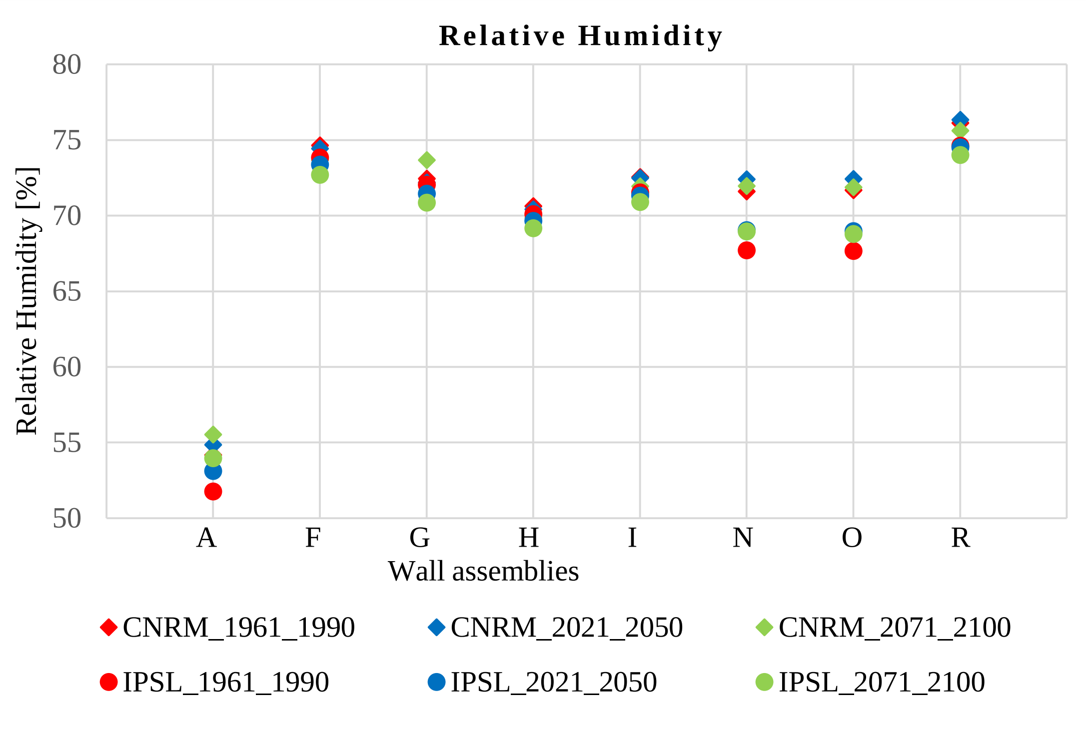


Figure 106: Average relative humidity for the future climate scenarios

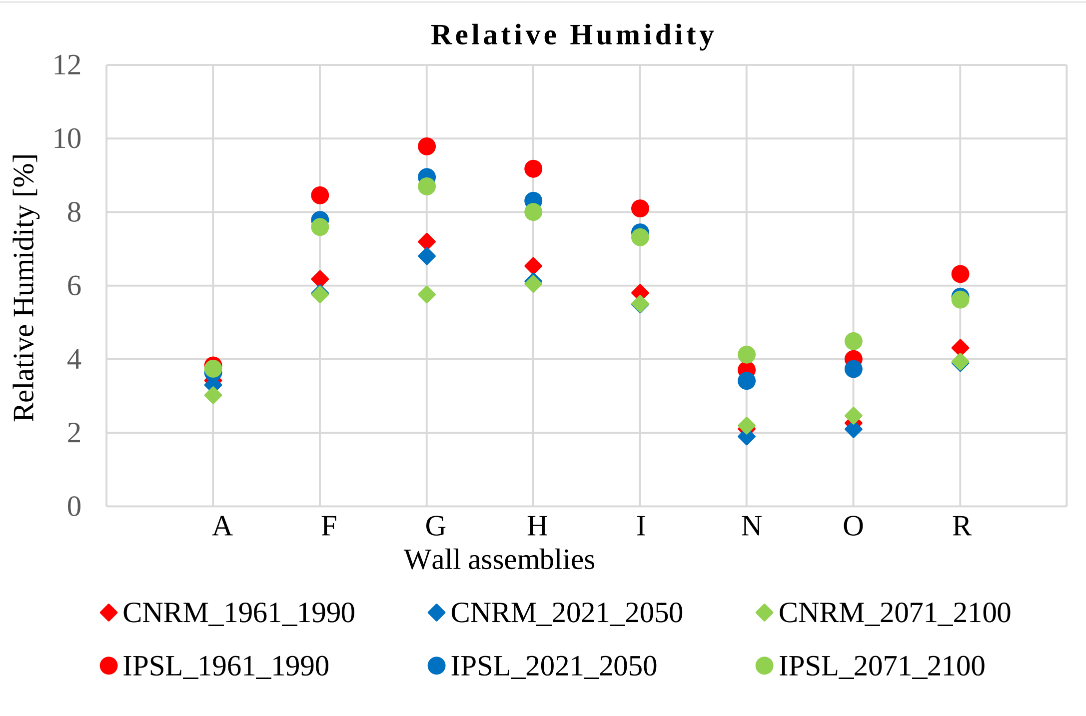


Figure 107: Standard deviation of the relative humidity for the future climate scenarios

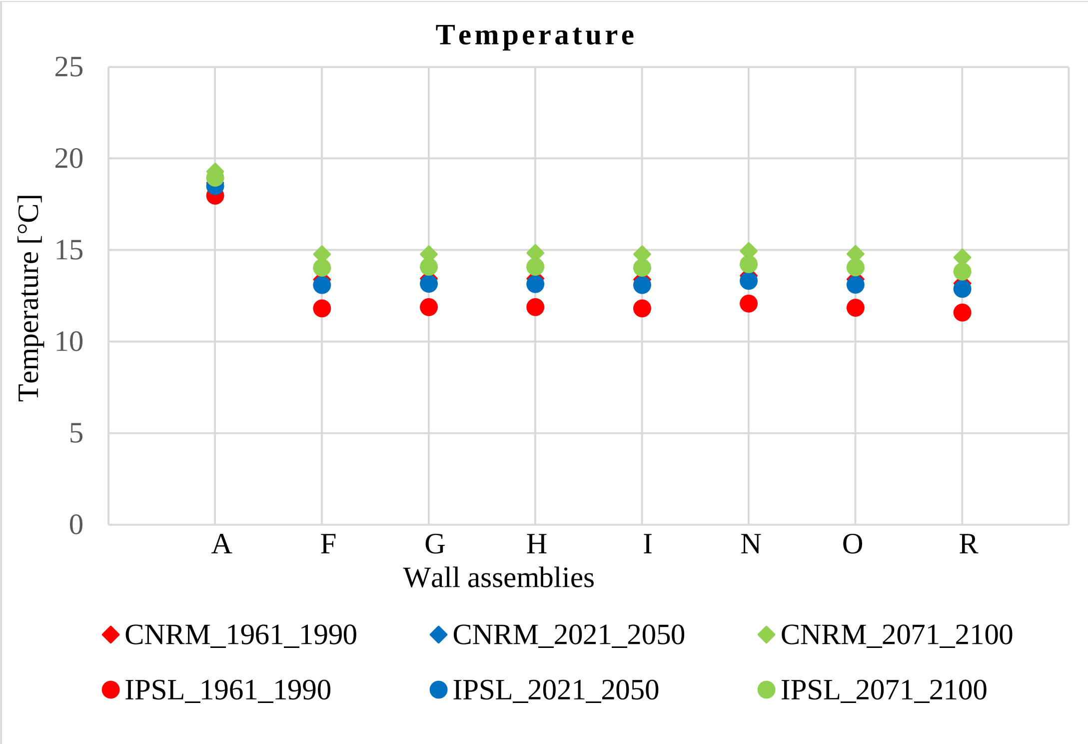


Figure 108: Average temperature for the future climate scenarios

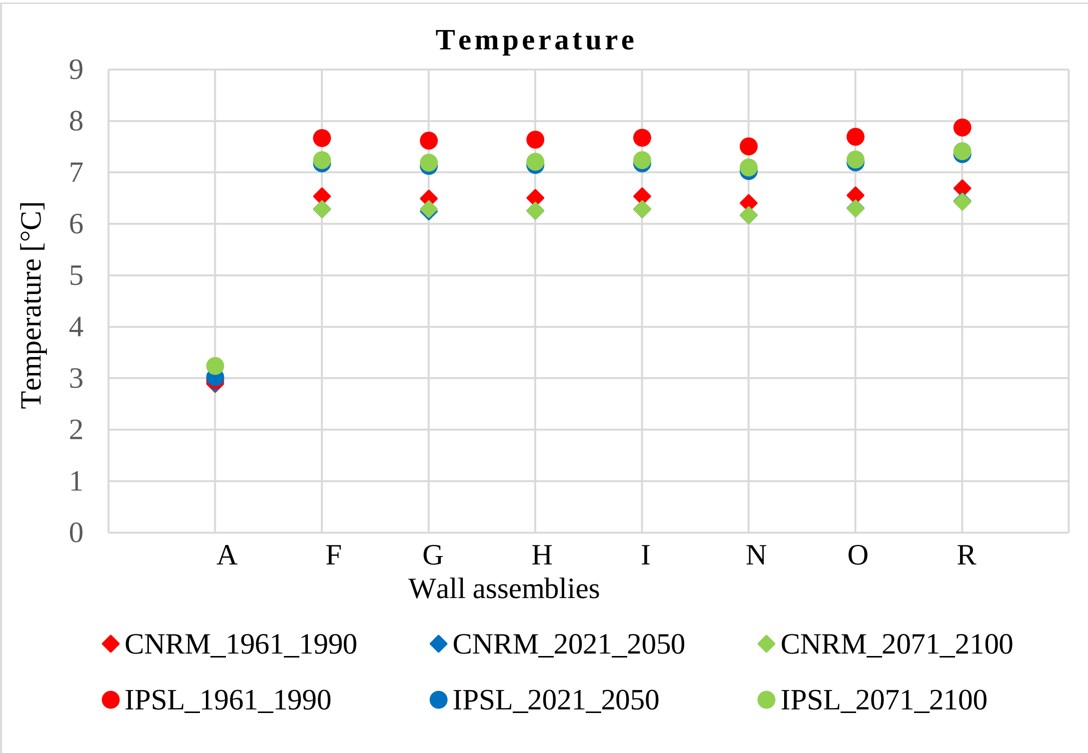


Figure 109: Standard deviation of the temperature for the future climate scenarios

In the same way as for the wall assemblies with the current climate data, the percentage of time where the preconditions for mould growth are met was calculated for the wall assemblies with each of the future climate scenarios. The results are shown in Table 19 below. Comparison of the future climate scenarios with the current climate showed, that the current climate data would pose a higher risk of mould growth due to interstitial condensation, as six out of seven wall assemblies experienced higher percentage of time where the preconditions were met with the current climate data compared to the future climate scenarios.

As for the different wall assemblies, the results showed that three out of four Calcium Silicate assemblies as well as the two smart vapour retarder assemblies (models G, H, I, N, and O) would have the lowest risk for mould growth, as the percentage of time where the preconditions are met lies in the range of 0.1 to 1% between the different assemblies. After further assessment of the individual future climate results for each of these five wall assemblies, it was determined that the models H, N, and O were the three most advantageous assemblies, as these assemblies showed the overall lowest percentage of time where the preconditions were met during the 30-year period. Although the two Calcium Silicate models, G and I, also showed a low percentage of time where the preconditions were met, only models H, N, and O were taken further to the thermal bridge simulation in HEAT2 and the energy simulations in Design Builder, Honeybee and IDA ICE.

Table 19: Percentage of time where the preconditions for mould growth are met for the coated South facing assemblies with the different future climate scenarios

	Percentage of time [%]							
Model ID	A	F	G	**H**	I	**N**	**O**	R
Current Climate Data for Gothenburg	0,0	4,7	2,0	**1,1**	1,5	**1,5**	**0,5**	2,7
CNRM_1961_1990	0,0	1,7	0,3	**0,4**	0,5	**0,3**	**0,3**	3,1
CNRM_2021_2050	0,0	1,9	0,3	**0,2**	0,4	**0,2**	**0,2**	2,5
CNRM_2071_2100	0,0	2,2	0,6	**0,5**	0,7	**0,8**	**1,0**	4,0
IPSL_1961_1990	0,0	2,3	0,9	**0,4**	0,4	**0,2**	**0,1**	5,4
IPSL_2021_2050	0,0	1,1	0,2	**0,4**	0,5	**0,3**	**0,2**	2,4
IPSL_2071_2100	0,0	1,5	0,3	**0,4**	0,5	**0,3**	**0,2**	2,3

6.1.4 Roof assemblies: mould growth

As mentioned earlier, the relative humidity and temperature fluctuations were studied at two monitor positions within each of the roof assemblies. The relative humidity results at the first monitor showed a large difference not only between the three existing roof assemblies (models A, B, and C), but also between the modified roof assemblies (models D, E, F, G, and H), as shown in Figure 110 below. Regarding the existing roof assemblies, at monitor one, both of the bitumen felt roofs (models A and B) would experience relative humidity levels above 75% for 40-60% of the time, while the less insulated copper roof assembly (model C) would only experience levels above 75% for around 10-15% of the time. The results furthermore showed that model B would experience 25% of the time to have relative humidity levels ranging from approximately 92 up to 100%. As for the modified roof assemblies, the results showed that the two ventilated roof assemblies with OSB and EPS on the exterior side of the air gap (models D and E) would both maintain relative humidity levels below 75% for more than 75% of the time during the 30-year period. The bitumen roof with the smart vapour retarder assembly (model G) also showed promising results, as it maintained humidity levels below 75% for almost the entire 30-year period. In contrast to the three before mentioned roof assemblies, the bitumen felt roof with the traditional vapour retarder as well as the exterior insulated concrete roof (models F and H), showed relative humidity levels above 75% for more than 60% and 40% of the time respectively. Although model H did not show promising results within the 30-year period, further assessment was carried out for this roof assembly as it showed a continuous decline in relative humidity during the period, which was not seen for the other failing assemblies. For this reason, the H70 model was developed, where the initial relative humidity was lowered from 80% to 70%, which was deemed quite possibly to achieve during the construction phase without too much of an effort. By simply lowering the initial relative humidity to 70%, the results for model H70 showed that the assembly would maintain a relative humidity levels below 75% for the entire 30-year period.

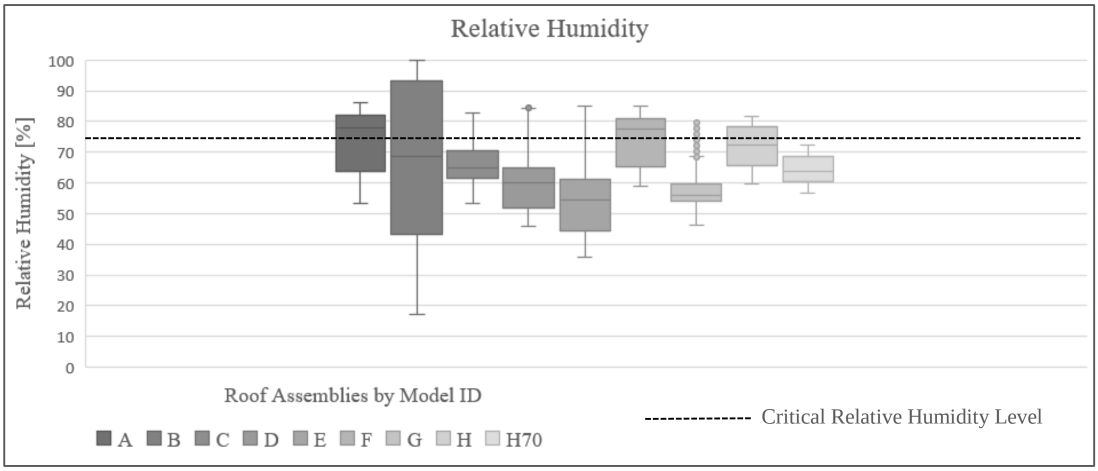


Figure 110: Relative humidity in the roof assemblies, at monitor position one

The simulation results showed that temperature range measured at monitor one differ greatly between the three existing roof assemblies, as shown in Figure 111 below. The temperature values range from 4 to 37 °C for model A, 17 to 28 °C for model B, while model C ranges from -8 to 35 °C. Compared to the existing roof assemblies, the modified assemblies do not differ nearly as much. The middle 50% of the temperature values primarily stay within the range 10-20 °C, while the upper and lower 25% differ between the assemblies. The ventilated roof assemblies tend to go as low as -3 °C, while the unventilated assemblies tend to go down to 3-7 °C. As for the upper 25%, five out of six modified roof assemblies tend to go as high as 35-38 °C, while the ventilated copper roof only reaches 31 °C.

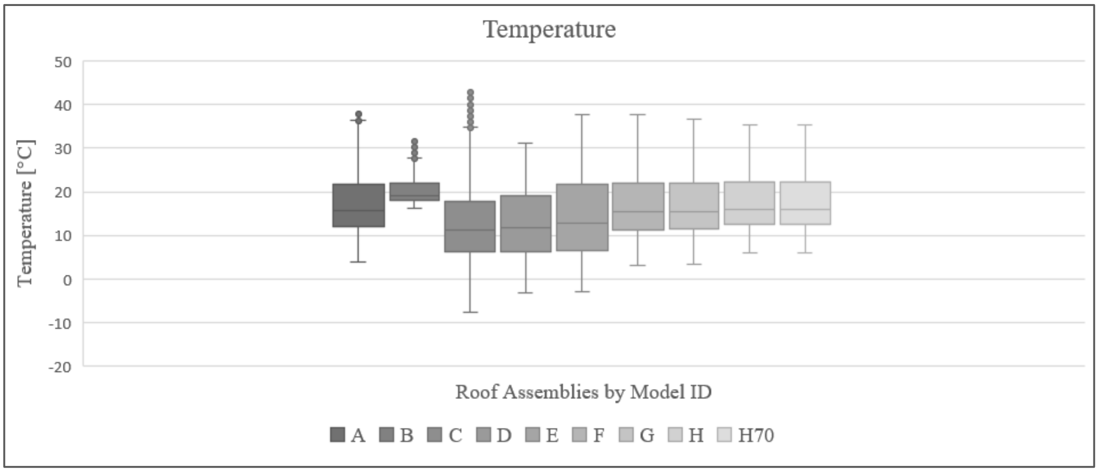


Figure 111: Temperature in the roof assemblies, at monitor position one

When compared to the relative humidity results at monitor one, then results at monitor two differ greatly between the roof assemblies, as shown in Figure 112. Two of the existing roof assemblies (models A and C) showed poor results, as the relative humidity values would range up to around 95% at times. Model A showed relative humidity levels above 75% for more than 30-40% of the time during the 30-year period, while model C maintained levels below 60% for more than 75% of the time. Despite maintaining low levels of relative humidity during the bigger part of the period, model C did show 10-15% of the time with levels above 75%. As for the modified roof assemblies, the results showed that the two ventilated roof assemblies would maintain levels below 65-70% for the bigger part of the period. In contrast to the ventilated roof assemblies, all the unventilated roof assemblies with the exception of the H70 model, showed relative humidity levels above 75% at times. The bitumen roof assembly with the traditional vapour retarder showed the higher values of all the modified roofs, with values ranging up to around 95% relative humidity, as well as having levels above 75% for more than 30-40% of the time. Regarding the temperature values at monitor two, the results showed only a small difference between the roof assemblies for the middle 50% of the temperature values, existing as well as modified assemblies, with only 3-4 °C, as shown in Figure 113.

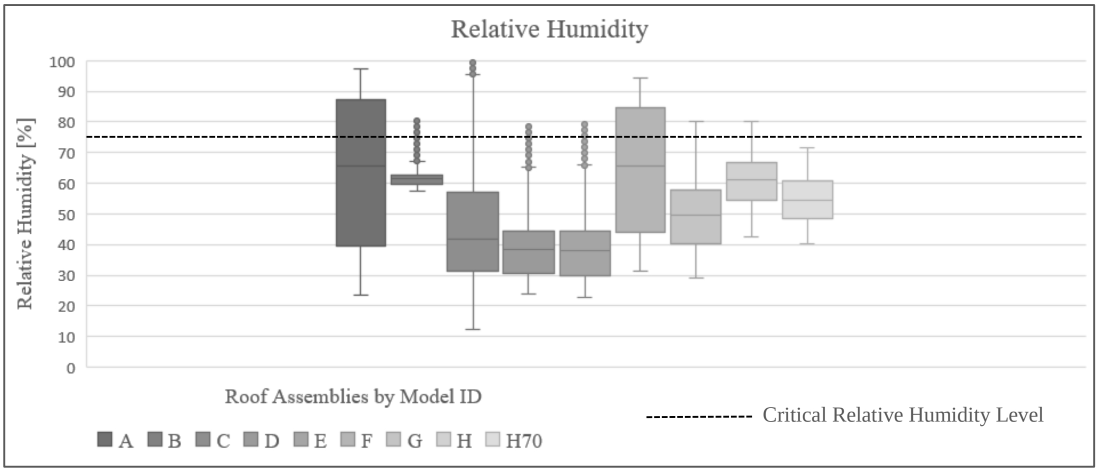


Figure 112: Relative humidity in the roof assemblies, at monitor position two

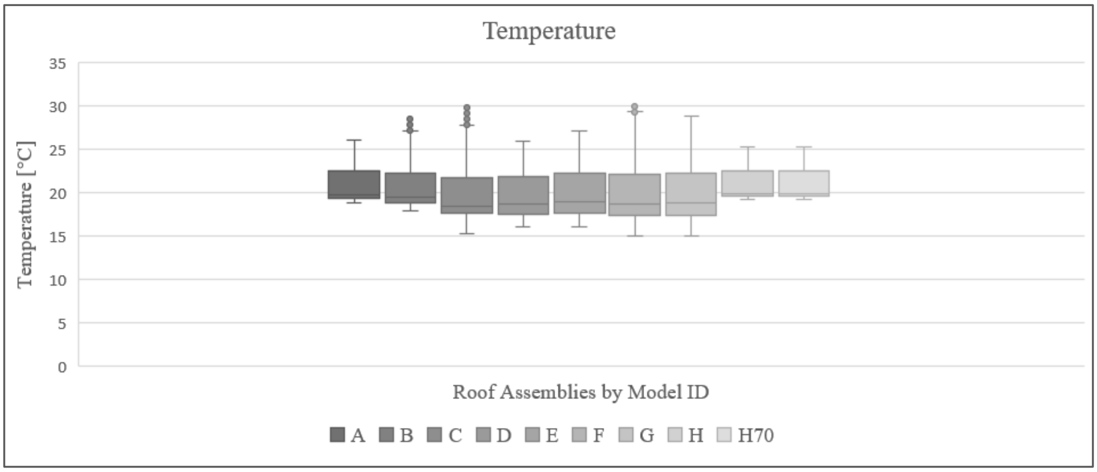


Figure 113: Temperature in the roof assemblies, at monitor position two

As shown in Table 20 below, the average relative humidity for all of the roof assemblies stay below the 75 % threshold at monitor one, however, models A, B, F, and H showed a high standard deviation bringing these models above the threshold at time. Models E and G showed the lowest relative humidity of 53% and 57% respectively, as well as a relatively low standard deviation of 9% and 5% respectively. As for the temperature values, five out of nine assemblies maintained an average temperature of approximately 17 °C, while three maintained temperatures of approximately 13-14 °C and the last assembly approximately 20 °C. Most assemblies showed a standard deviation for the temperature values of 6 to 9 °C, except for model B, which showed only 3 °C.

At monitor two, the average relative humidity for the roof assemblies ranged between 38% and 65%, where models A, B, F, and H showed the highest values, all above 60% relative humidity, as shown in Table 21. The standard deviation ranged from 4% to 23%, where models A, C, and F showed the highest values, all within 19% to 23%. Models D, E, and H70 showed the lowest average relative humidity with 38%, 38% and 55% respectively, while having a standard deviation of 8%, 9%, and 8% respectively. As for the temperature values, all roof assemblies maintained an average temperature around 20-21 °C, with a standard deviation of 1.7-3.1 °C.

Table 20: Average and standard deviation for the relative humidity and temperature at monitor position one

	Relative Humidity [%]		Temperature [°C]	
Model ID	Average	Standard deviation	Average	Standard deviation
A	73	10	17,3	6,7
B	68	25	20,3	3,0
C	66	6	12,9	8,9
D	59	7	12,6	7,3
E	53	9	14,4	8,7
F	74	8	17,0	6,8
G	57	5	17,0	6,6
H	72	7	17,5	5,9
H70	64	4	17,5	5,9

Table 21: Average and standard deviation for the relative humidity and temperature at monitor position two

	Relative Humidity [%]		Temperature [°C]	
Model ID	Average	Standard deviation	Average	Standard deviation
A	64	23	20,9	1,8
B	62	4	20,6	2,3
C	47	19	19,7	2,7
D	38	8	19,6	2,5
E	38	9	20,0	2,7
F	65	20	19,9	3,1
G	49	10	19,9	3,0
H	61	8	20,9	1,7
H70	55	8	20,9	1,7

In the same way as with the wall assemblies, Folos 2D visual mould chart was also used to calculate the percentage of time where the preconditions for mould growth are met for each of the roof assemblies, as mentioned in section 5.5.6.3. The results for the roof assemblies showed, that the two ventilated roof assemblies as well as the smart vapour retarder assembly and the exterior insulated concrete assembly (models D, E, G, and H70) resulted in the lowest percentage of time where the preconditions for mould growth were met at both monitor one and two. At monitor one, the results ranged between 0% and 3.5% of the time, while at monitor two, the results ranged between 0 and 0.3% of the time, shown in Table 22 below. Models A and F, showed highest percentage of time at both monitor positions, with values around 39-40% of the time, while model H showed the highest percentage of time where the preconditions for mould growth were met, at one monitor position, with almost 94%.

Table 22: Percentage of time where the preconditions for mould growth are met for the uncoated North facing assemblies

	Percentage of time [%]								
Model ID	A	B	C	D	E	F	G	H	H70
Monitor 1	47,7	40,6	23,3	3,5	3,2	47,2	2,5	93,8	0
Monitor 2	39,8	8,6	17,5	0,2	0,2	38,8	0,3	14,2	0

6.1.5 Roof assemblies: future climate scenarios

In the same way as with the current climate data, two monitor positions were studies for the roof assemblies with the future climate scenarios. The assemblies were as mentioned earlier, the two ventilated roof assemblies, the smart vapour retarder assembly as well as the exterior insulated concrete roof with reduce initial relative humidity (models D, E, G, and H70). When comparing the future climate scenarios with the current climate data at monitor one, the results showed an increase in the relative humidity for the two ventilated roof assemblies (models D and E), as shown in Figure 114-119. The biggest increase for the two ventilated roof assemblies occurred with the CNRM climate model, with a small increase occurring between each of the time periods. In contrast to the two ventilated roof assemblies, the smart vapour retarder assembly and the exterior insulated concrete roof (models G and H70) did not experience much change between any of the future climate scenarios. In general, the two unventilated roof assemblies showed lower levels of relative humidity in comparison to the two ventilated roof assemblies. Both of the unventilated roof assemblies maintain relative humidity levels below the 75% threshold for the bigger part of the 30-year period, while the two ventilated roof assemblies at times experience relative humidity levels between 75% and 88%.

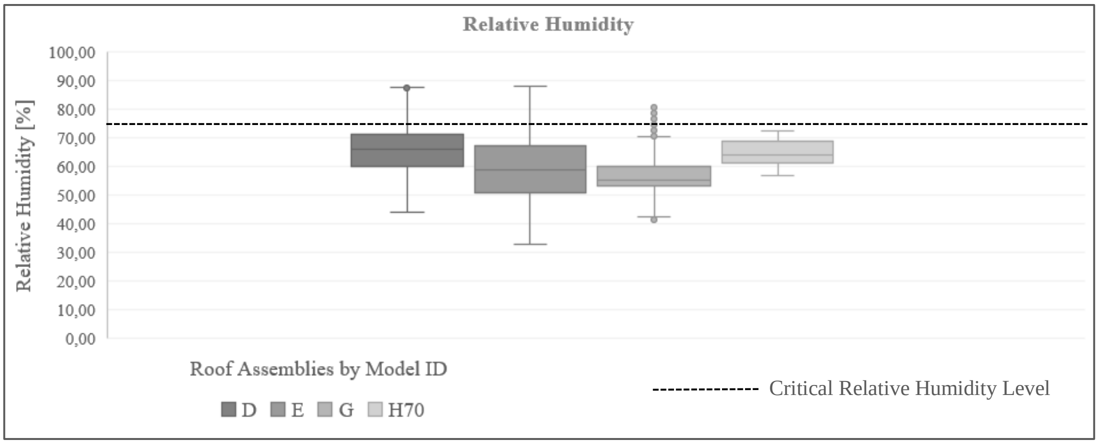


Figure 114: Relative humidity in the roof assemblies (monitor position one, climate file CNRM_1961_1990)

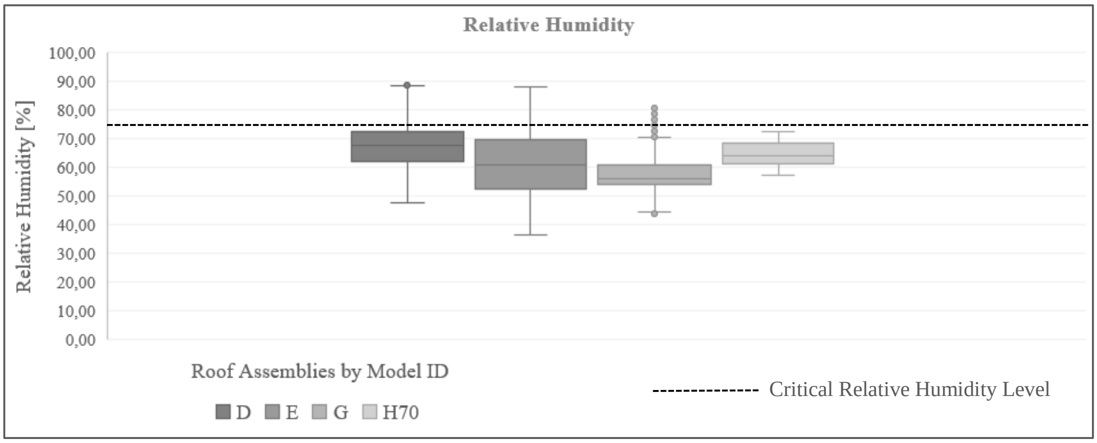


Figure 115: Relative humidity in the roof assemblies (monitor position one, climate file CNRM _2021_2050)

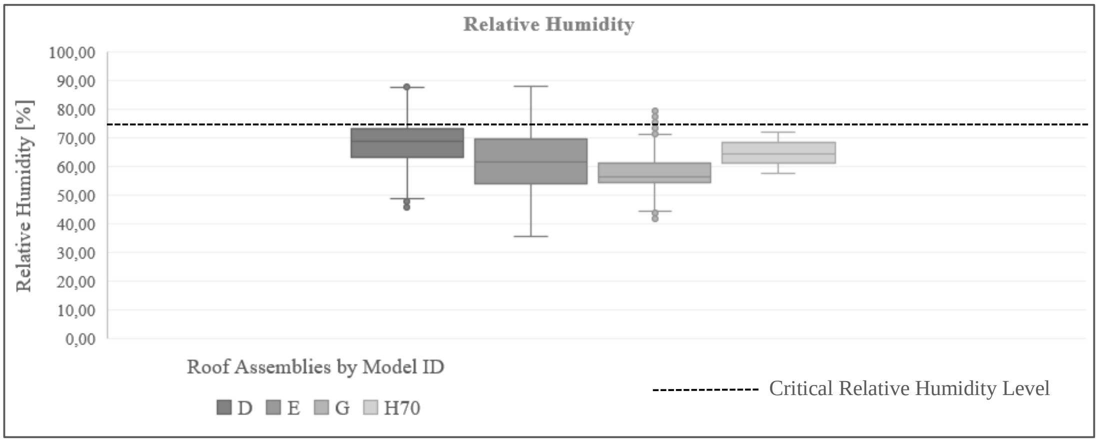


Figure 116: Relative humidity in the roof assemblies (monitor position one, climate file CNRM _2071_2100)

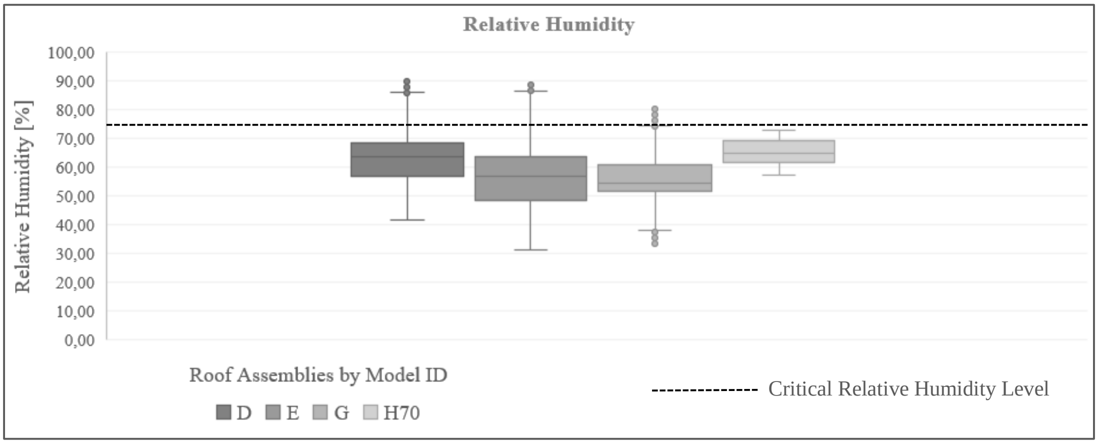


Figure 117: Relative humidity in the roof assemblies (monitor position one, climate file IPSL _1961_1990)

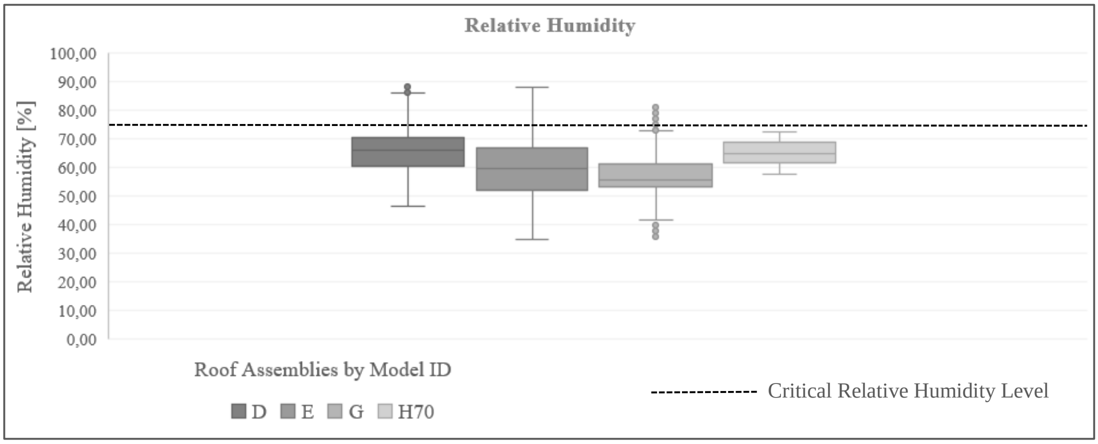


Figure 118: Relative humidity in the roof assemblies (monitor position one, climate file IPSL _2021_2050)

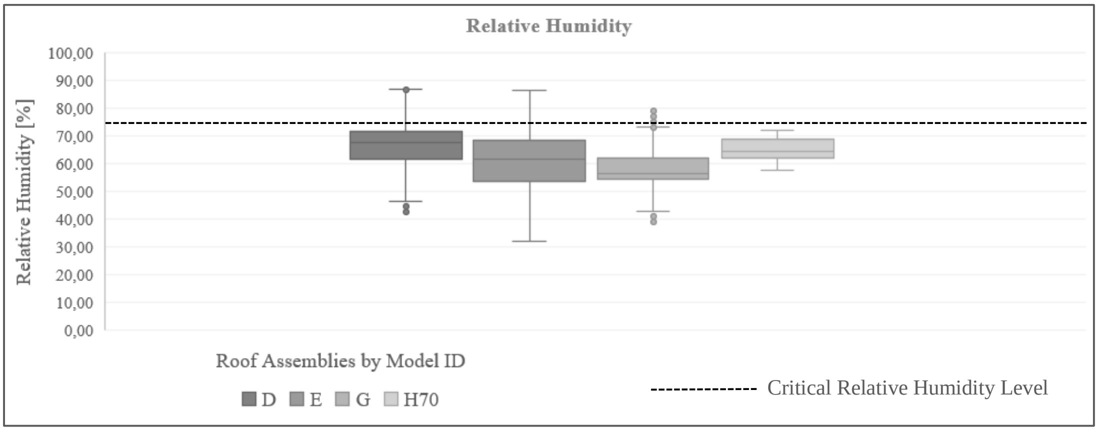


Figure 119: Relative humidity in the roof assemblies (monitor position one, climate file IPSL _2071_2100)

When compared to the current climate data, the temperature results for the roof assemblies with the future climate scenarios at monitor one primarily showed a decrease in the lower part of the temperature values, as shown in Figure 120-125. Which showed to be worst for the IPSL climate model, where the lowest measured temperatures for the ventilated roofs were down to -15 °C to -18 °C, and for the unventilated roofs down to -2 °C to -5 °C. For the current climate data, the lowest measured temperatures were -3 °C for the ventilated roofs, and 3 °C to 6 °C for the unventilated roofs. For the CNRM climate model, the lowest measured temperatures for the ventilated roofs were down to -8 °C to -11 °C, and for the unventilated roofs down to -2 °C to 2 °C. Common for both the CNRM- and the IPSL climate model was that between the three time periods the lowest measured temperatures would increase with a few degrees. An example of the increase in the lowest temperatures, can be seen by studying how the lower quartile for model D with the CNRM climate model change between the three time periods, as shown in Figure 120-122. The lowest temperatures for model D shows an increase from -11 °C in 1961-1990 to -10 °C in 2021-2050, and then again to -8 °C in 2071-2100.

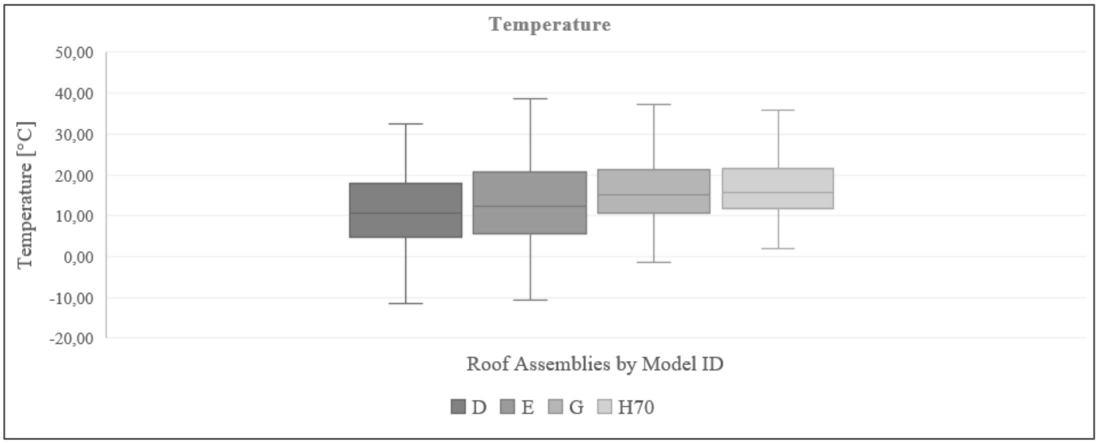


Figure 120: Temperature in the roof assemblies (monitor position one, climate file CNRM_1961_1990)

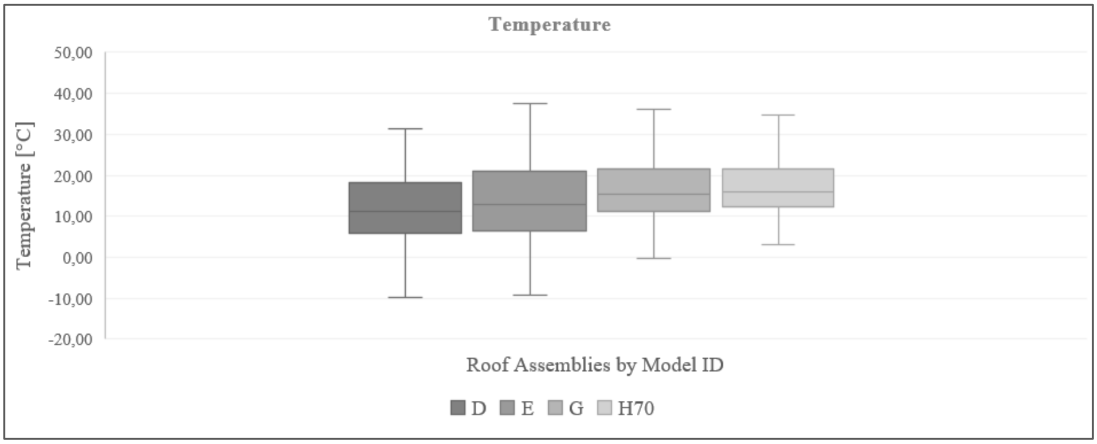


Figure 121: Temperature in the roof assemblies (monitor position one, climate file CNRM_2021_2050)

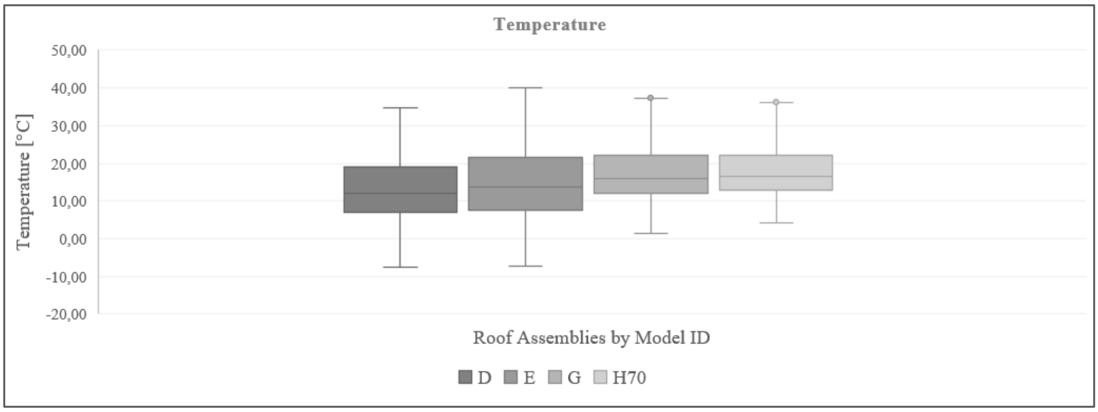


Figure 122: Temperature in the roof assemblies (monitor position one, climate file CNRM_2071_2100)

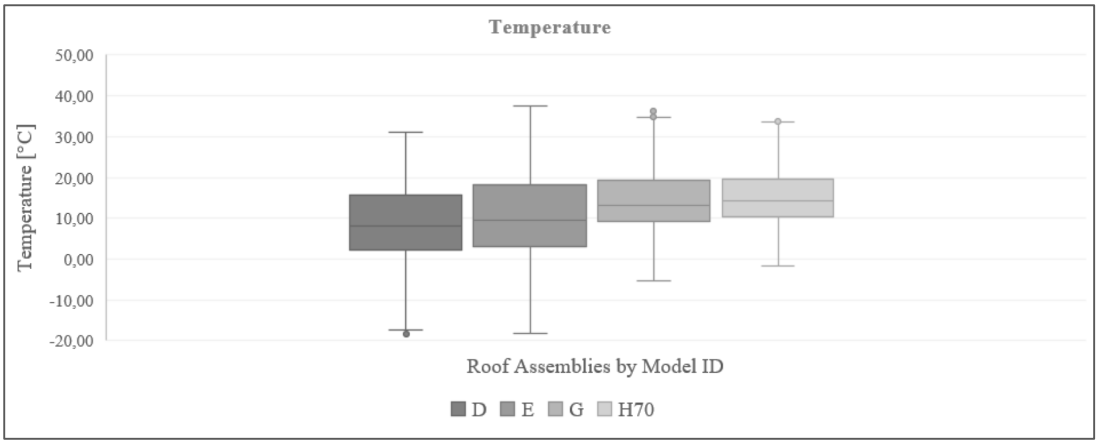


Figure 123: Temperature in the roof assemblies (monitor position one, climate file IPSL_1961_1990)

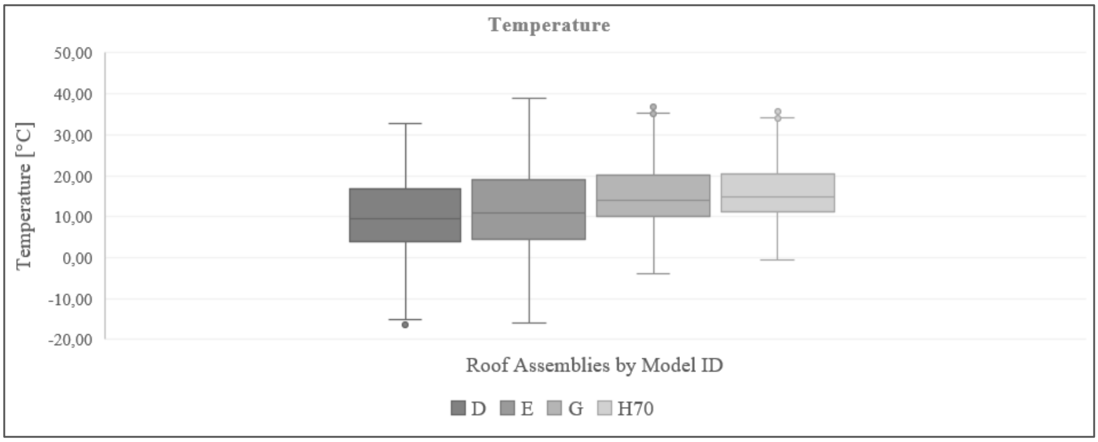


Figure 124: Temperature in the roof assemblies (monitor position one, climate file IPSL_2021_2050)

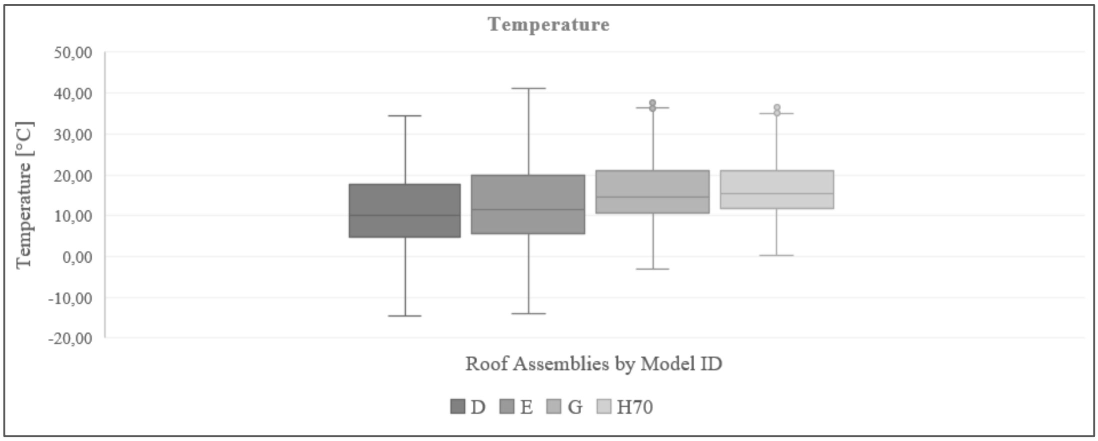


Figure 125: Temperature in the roof assemblies (monitor position one, climate file IPSL_2071_2100)

As seen for monitor one, primarily the two ventilated roof assemblies (models D and E) showed an increase in the relative humidity, while the two unventilated roof assemblies (models G and H70) maintained relatively similar results as for the current climate data, as shown in Figure 126-131. And in the same way as for monitor one, the biggest increase in relative humidity for the two ventilated roof assemblies occurred with the CNRM climate model. In contrast to monitor one, the results showed that all four roof assemblies would maintain relative humidity levels below 70% for the vast majority of the time during the 30-year period, which was common for all the future climate scenarios.

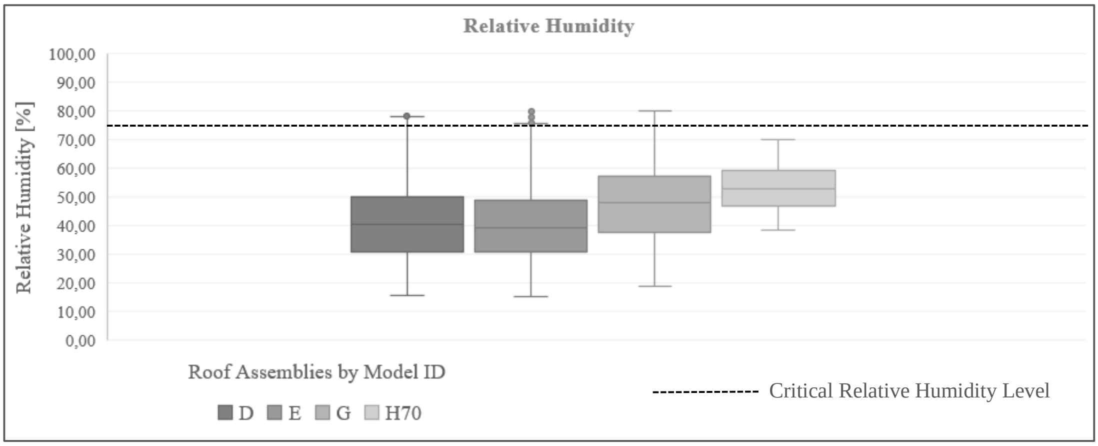


Figure 126: Relative humidity in the roof assemblies (monitor position two, climate file CNRM_1961_1990)

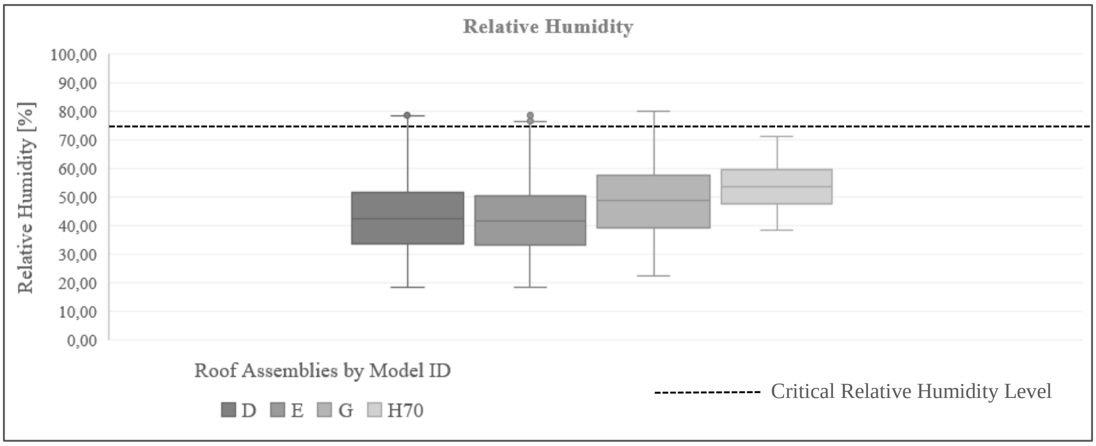


Figure 127: Relative humidity in the roof assemblies (monitor position two, climate file CNRM_2021_2050)

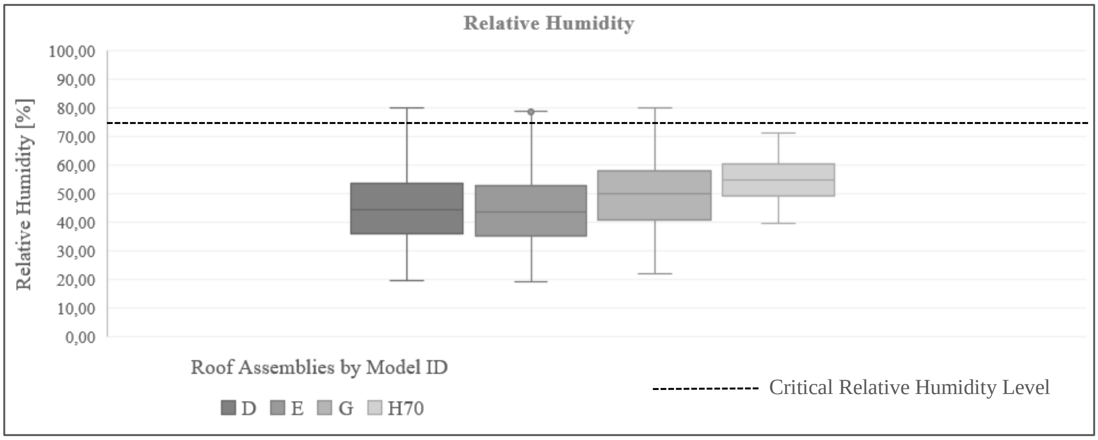


Figure 128: Relative humidity in the roof assemblies (monitor position two, climate file CNRM_2071_2100)

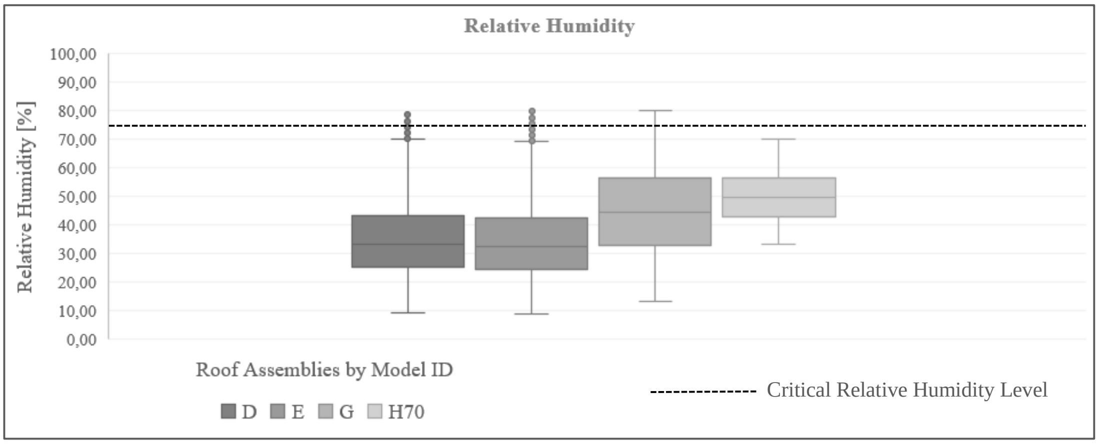


Figure 129: Relative humidity in the roof assemblies (monitor position two, climate file IPSL_1961_1990)

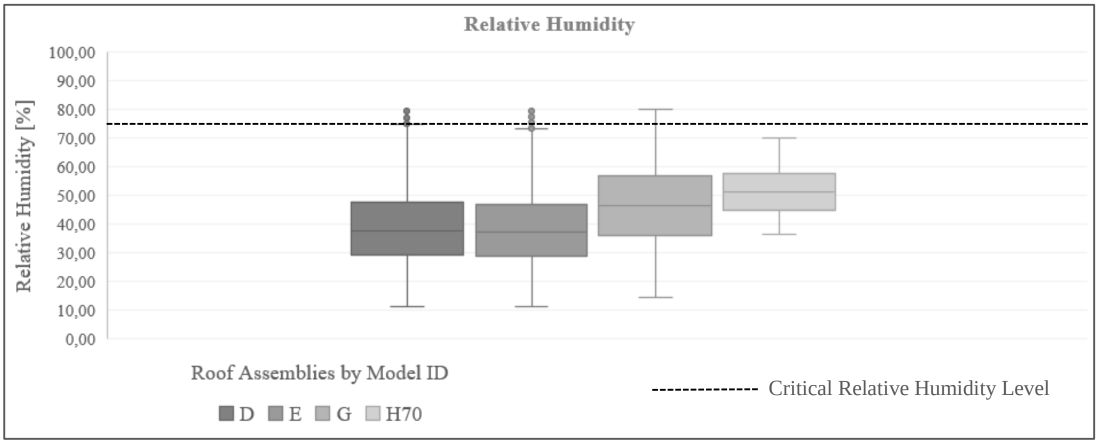


Figure 130: Relative humidity in the roof assemblies (monitor position two, climate file IPSL_2021_2050)

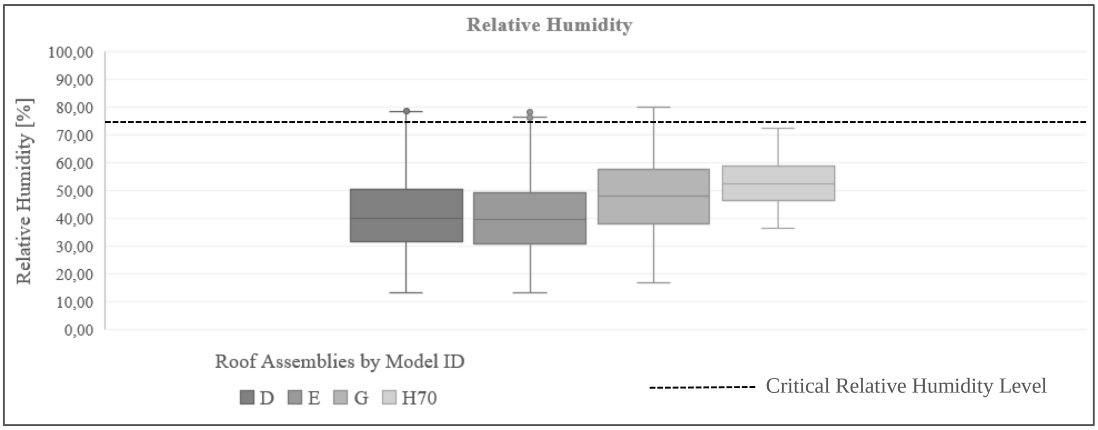


Figure 131: Relative humidity in the roof assemblies (monitor position two, climate file IPSL_2071_2100)

When compared to the current climate date, the temperature values measure at monitor two showed very little change for the upper 75% of the values, while the lower 25% showed a small decrease in the lowest temperature values, as shown in Figure 132-137. The largest decrease occurred with the IPSL climate model. The lowest temperature values showed to decrease from 15-17 °C down to 13-14 °C for the IPSL climate model, while for the CNRM climate model the temperature showed a decrease down to 14-15 °C.

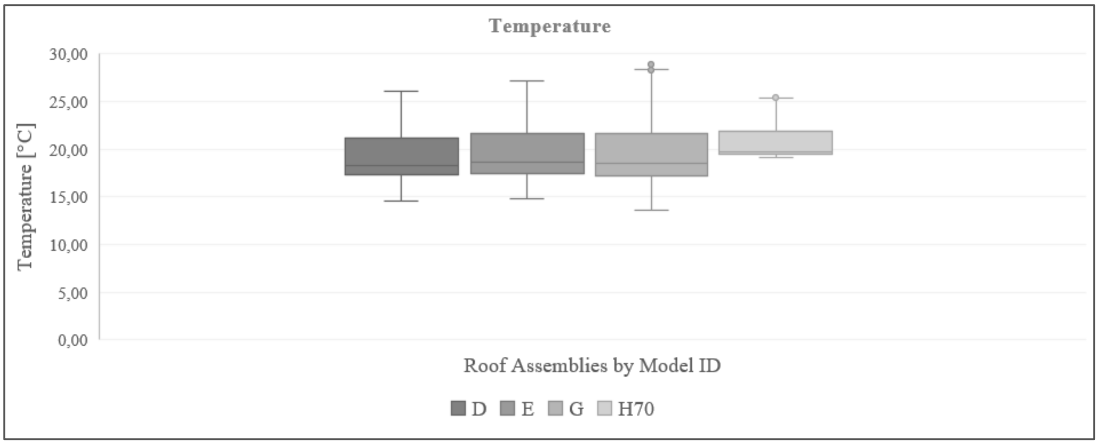


Figure 132: Temperature in the roof assemblies (monitor position two, climate file CNRM_1961_1990)

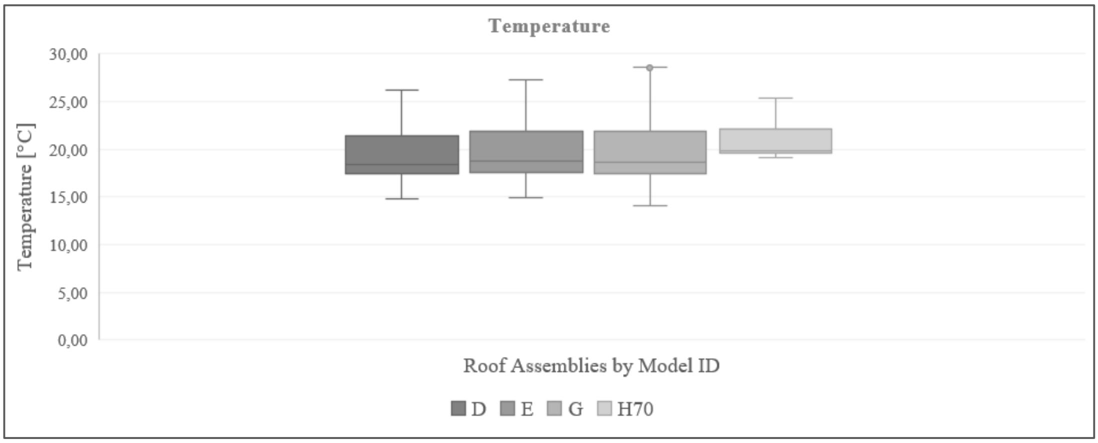


Figure 133: Temperature in the roof assemblies (monitor position two, climate file CNRM_2021_2050)

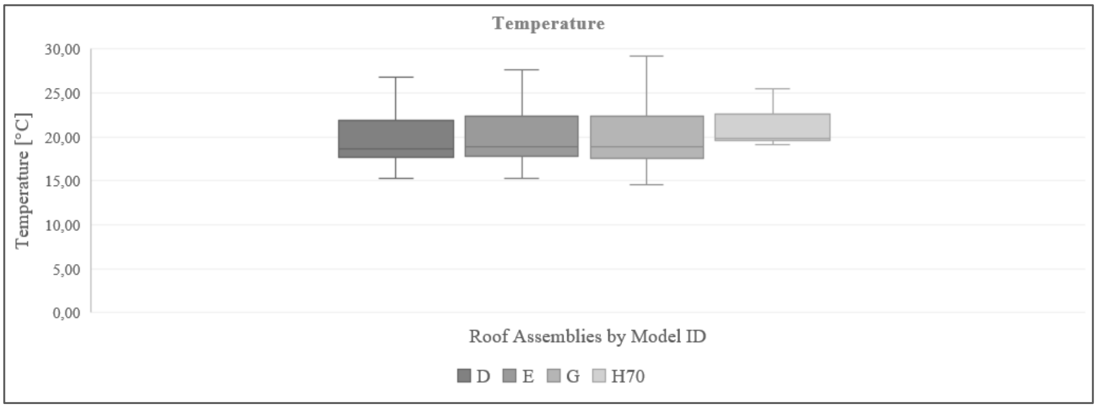


Figure 134: Temperature in the roof assemblies (monitor position two, climate file CNRM_2071_2100)

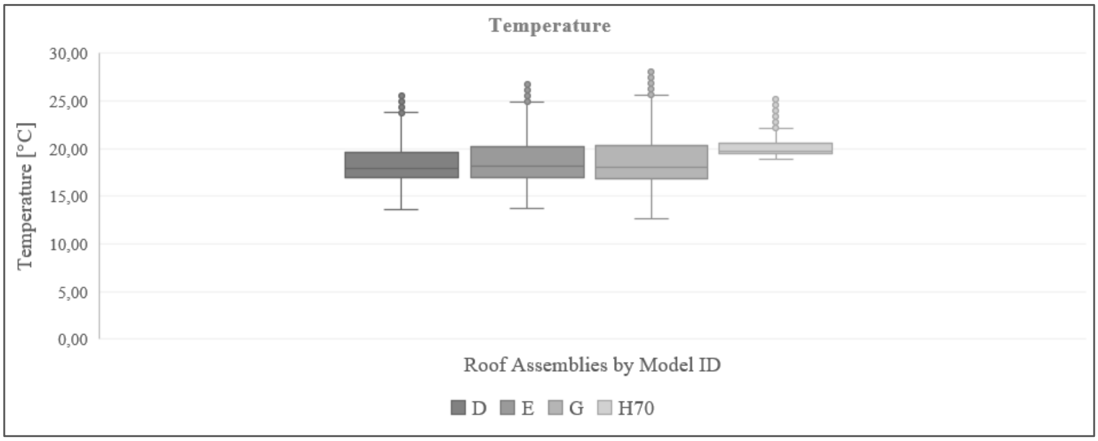


Figure 135: Temperature in the roof assemblies (monitor position two, climate file IPSL_1961_1990)

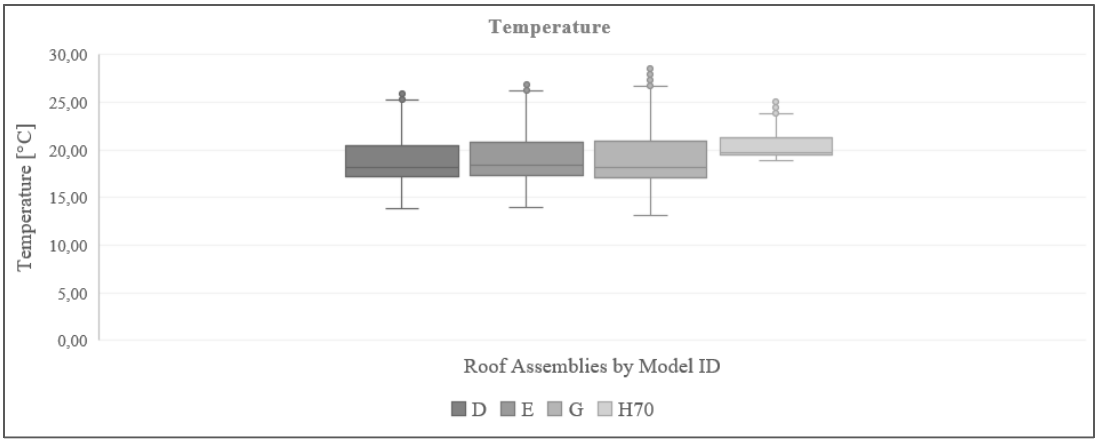


Figure 136: Temperature in the roof assemblies (monitor position two, climate file IPSL_2021_2050)

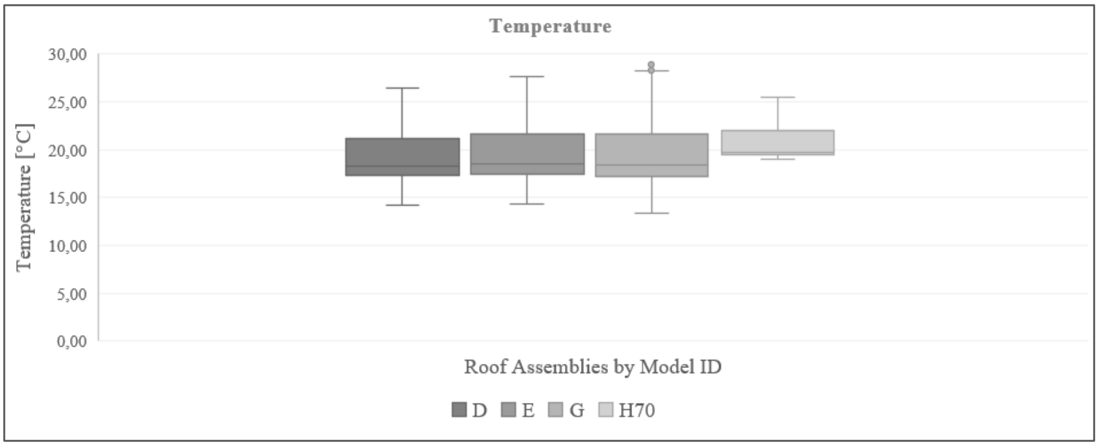
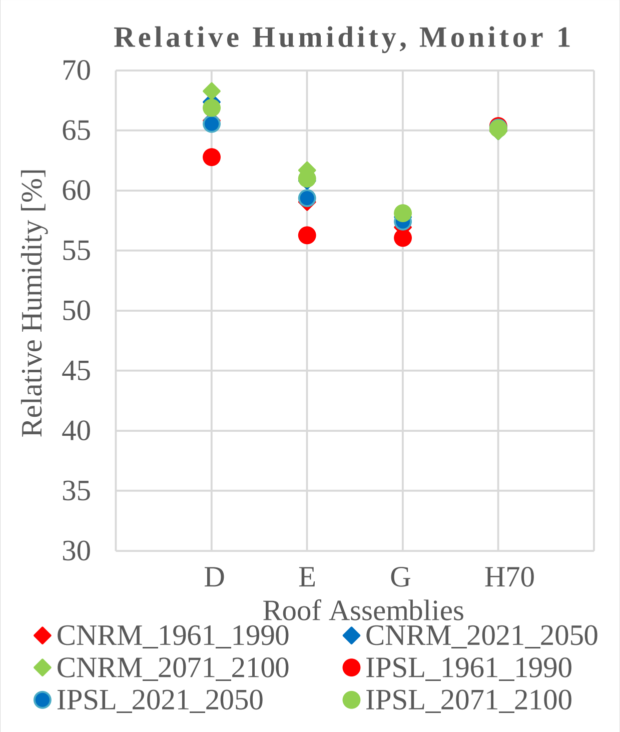


Figure 137: Temperature in the roof assemblies (monitor position two, climate file IPSL_2071_2100)

When compared with the average relative humidity for the current climate data at monitor one, the results showed an increase for the two ventilated roof assemblies (models D and E) by 5-10% between the different climate scenarios. In contrast, the unventilated roof assemblies (models G and H70) showed hardly any change in the relative humidity at monitor one, as shown in Figure 138. As seen for monitor one, the average relative humidity also showed an increase for the two ventilated roof assemblies at monitor two, while the two unventilated roof assemblies experienced a small decrease. The decrease experienced by the two unventilated roof assemblies differed between the reference periods and the future climate scenarios, the biggest decrease was noticed for the IPSL climate model in the period 1961-1990, with a 5% decrease, as shown in Figure 138. As for the standard deviation of the relative humidity at monitor one, the results showed little changed between the current climate data and the future climate scenarios. The biggest difference between the current climate data and the future climate scenarios was noticed for model G, which showed an increase of 1-2% between the different climate scenarios, as shown in Figure 139. At monitor two, the two ventilated roof assemblies showed a small increase in the standard deviation of 2-3%, while the smart vapour retarder assembly showed an increase in the standard deviation of 1-4%.



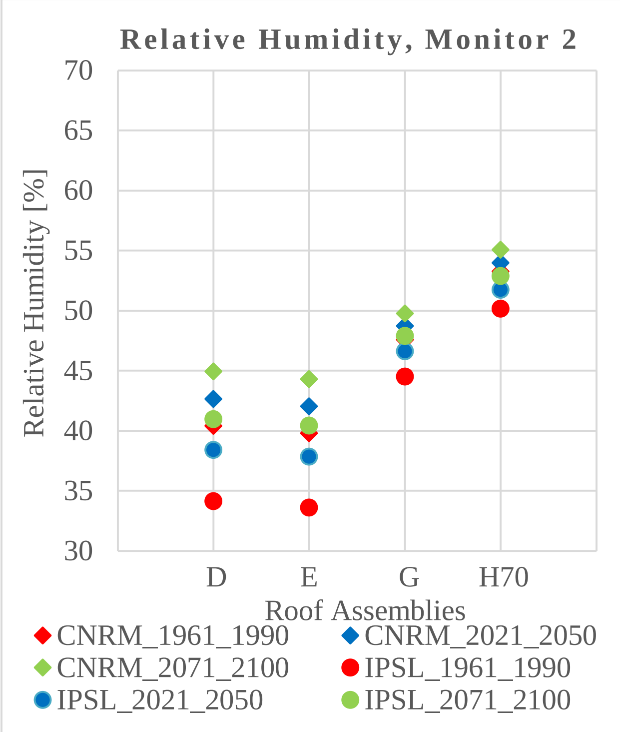
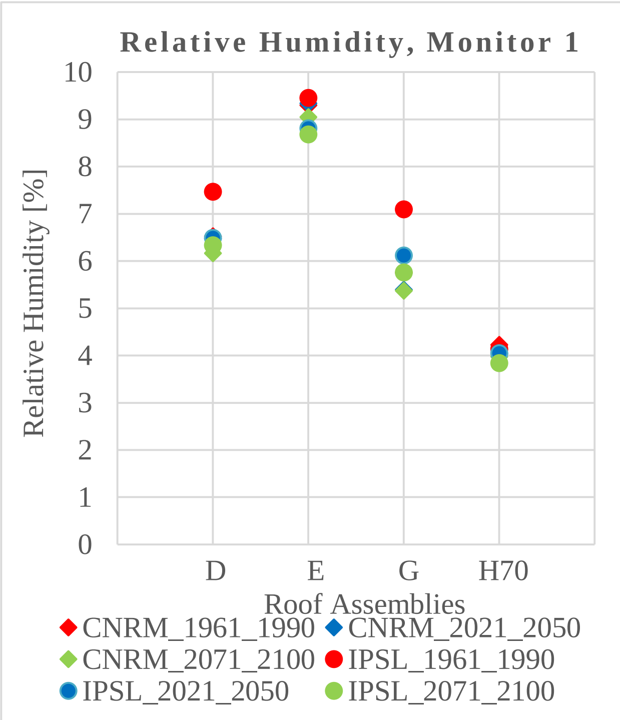


Figure 138: Average relative humidity for the future climate scenarios at monitor 1 and 2



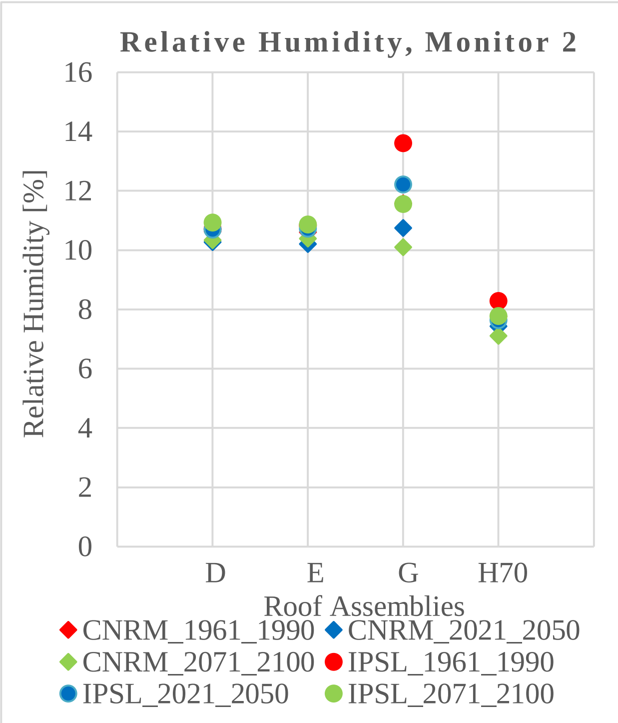


Figure 139: Standard deviation of the relative humidity for the future climate scenarios at monitor 1 and 2

Regarding the average temperatures, the results showed that all roof assemblies at monitor one would experience a small decrease in the temperatures by 3-4 °C, while the average temperatures for monitor two did not show any changes from the current climate data, as shown in Figure 140. For the standard deviation at monitor one, the results showed a small increase of by 1-2 °C for the two ventilated roof assemblies, while the two unventilated roof assemblies did not show any changes, as shown in Figure 140. As seen for the average temperatures at monitor two, no major changes occurred for the standard deviation of the temperatures at monitor two.

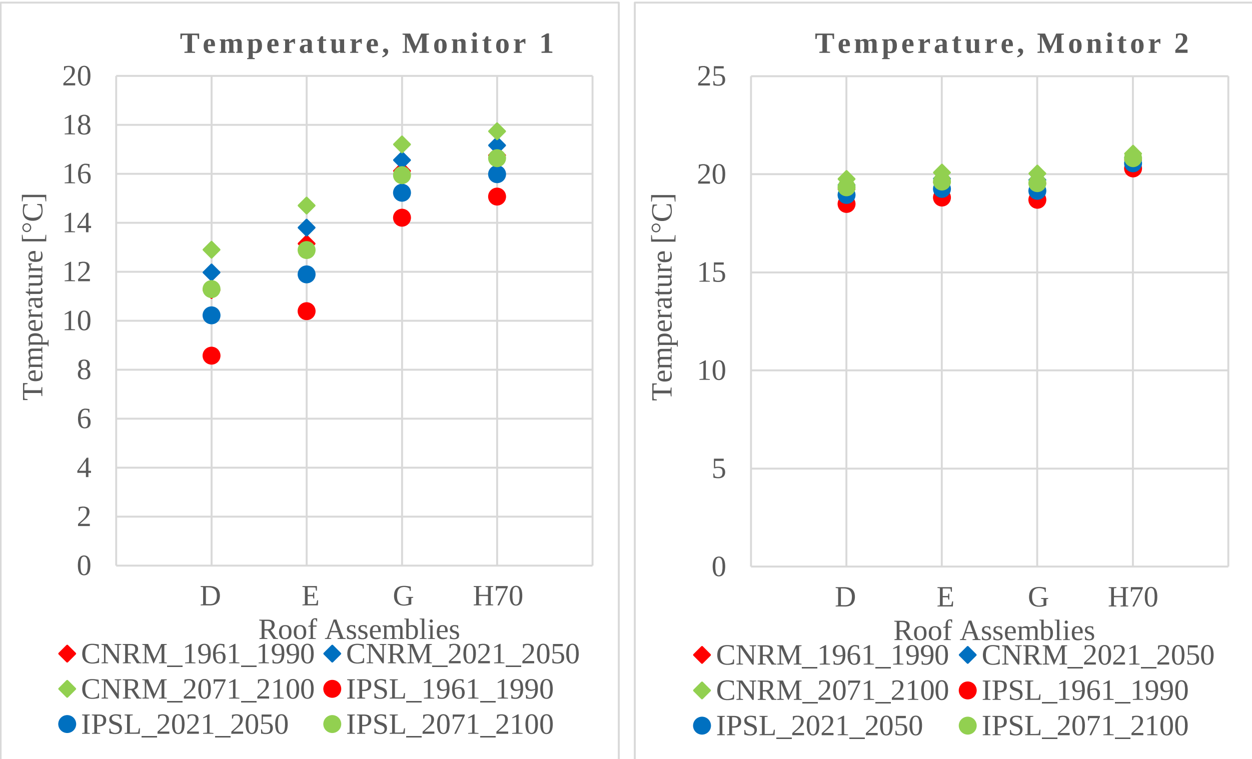
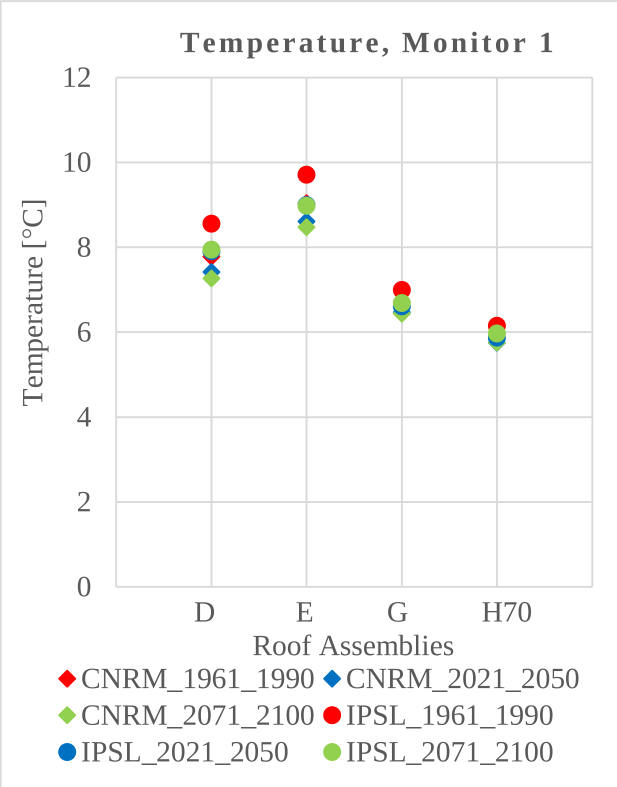


Figure 140: Average temperature for the future climate scenarios at monitor 1 and 2



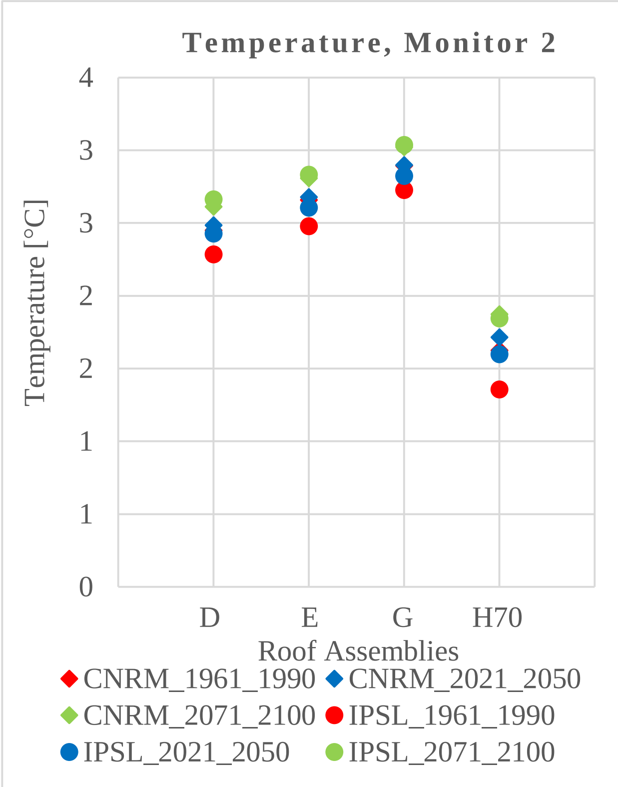


Figure 141: Standard deviation of the temperature for the future climate scenarios at monitor 1 and 2

In the same way as for the current climate data, the percentage of time where the preconditions for mould growth are met was calculated for the roof assemblies with the future climate scenarios by using the Folos 2D visual mould chart, the results are shown in Table 23 below. The results showed only little difference between the current climate data and the future climate scenarios at monitor two, with the biggest increase occurring in model G with the IPSL climate model in the time period 1961-1990, with an increase of 0.5%. The difference showed to be a bit bigger at monitor one, where the results showed both increases and decrease occurring between the different time periods for the two climate models. The biggest decrease occurred between the current climate model and the IPSL climate model in the time period 2021-2050, with a decrease of 1.7% for model D. While the biggest increase occurred between the current climate model and the CNRM climate model in the time period 1961-1990, with an increase of 1%. Of all the assemblies, the exterior insulated concrete roof with reduce initial relative humidity showed the overall best performance, with 0% of the time at both monitor positions, for all the climate scenarios simulated within this study.

Table 23: Percentage of time where the preconditions for mould growth are met for the roof assemblies with the different future climate scenarios

	Percentage of time [%]							
	Monitor 1				Monitor 2			
Model ID	D	E	G	H70	D	E	G	H70
Current Climate Data for Gothenburg	3,5	3,2	2,5	0,0	0,2	0,2	0,3	0,0
CNRM _1961_1990	3,8	3,8	3,5	0,0	0,2	0,2	0,4	0,0
CNRM _2021_2050	2,7	2,6	3,1	0,0	0,2	0,3	0,4	0,0
CNRM _2071_2100	3,1	3,1	2,9	0,0	0,1	0,2	0,2	0,0
IPSL _1961_1990	2,6	2,4	2,8	0,0	0,1	0,1	0,8	0,0
IPSL _2021_2050	1,8	1,9	2,8	0,0	0,1	0,1	0,3	0,0
IPSL _2071_2100	3,7	3,6	3,2	0,0	0,1	0,2	0,1	0,0

6.2 Thermal bridging simulations

It was determined by the WUFI simulations that the Calcium Silicate Washington assembly, the aerogel and smart vapour retarder assembly, as well as the glass wool and smart vapour retarder assembly (models H, N, and O) would carry the lowest risk with respect mould growth and freeze thaw damage. The effect of the thermal bridges simulated in HEAT2 was therefore carried out only for these three wall assemblies. In addition to the three wall assemblies, also the exterior EPS insulated concrete roof assembly (model H70) was included in the HEAT2 simulations, which was used for the roof eave junction together with each of the three wall assemblies. Only roof assembly H70 was simulated in HEAT2. As the energy simulation software would only accept one Ψ-value for each junction type. The exterior EPS insulated concrete roof assembly was chosen, as this type was predominantly used in the two buildings. Despite only calculating the Ψ-value for the exterior EPS insulation concrete roof assembly, also the ventilated copper roof assembly and the smart vapour retarder roof assembly (models D and G) was included in the energy simulations. After simulating the junctions both as a whole and as separate parts, the q-values and lengths were obtained for each wall assembly. The results from the HEAT2 simulations are shown in Table 24-26 below.

Table 24: HEAT2 simulation results for wall assembly H

Junction Type	**q_{tot} [W/m]**	**q_1 [W/m]**	**q_2 [W/m]**	**L_1 [m]**	**L_2 [m]**	**ΔT [°C]**
Intermediate Floor	43.39	32.68	-	-	-	30
Wall Corner (Exterior)	58.33	28.63	28.63	2.87	2.87	30
Roof Eave	32.48	12.24	9.65	1.41	4.87	30
Window-Wall	138.57	127.98	3.25	-	-	30

Table 25: HEAT2 simulation results for wall assembly N

Junction Type	**q_{tot} [W/m]**	**q_1 [W/m]**	**q_2 [W/m]**	**L_1 [m]**	**L_2 [m]**	**ΔT [°C]**
Intermediate Floor	38.71	26.05	-	-	-	30
Wall Corner (Exterior)	47.96	23.77	23.77	2.93	2.93	30
Roof Eave	30.16	10.87	9.78	1.41	4.93	30
Window-Wall	138.11	127.98	2.71	-	-	30

Table 26: HEAT2 simulation results for wall assembly O

Junction Type	**q_{tot} [W/m]**	**q_1 [W/m]**	**q_2 [W/m]**	**L_1 [m]**	**L_2 [m]**	**ΔT [°C]**
Intermediate Floor	47.58	36.62	-	-	-	30
Wall Corner (Exterior)	64.12	32	32	2.93	2.93	30
Roof Eave	34.39	15.37	9.78	1.41	4.93	30
Window-Wall	138.71	127.98	3.78	-	-	30

After the q-values and lengths were obtained from the HEAT2 simulations, the hand calculations were carried out for each of the junctions to obtain the Ψ-values. The hand calculations used in this study are all shown below, separated by assembly, and the resulting Ψ-values are shown in Table 27.

Wall assembly H:

Intermediate floor junction

$$\Psi = \frac{43.39-32.68}{30} \tag{8}$$

Wall corner junction

$$\Psi = \frac{(58.33)\cdot(2.87+2.87)-(28.63\cdot2.87+28.63\cdot2.87)}{30\cdot(2.87+2.87)} \tag{9}$$

Roof eave junction

$$\Psi = \frac{32.48\cdot(1.41+4.87)-(14.24\cdot1.41+9.65\cdot4.87)}{30\cdot(1.41+4.87)} \tag{10}$$

Window-wall junction

$$\Psi = \frac{138.57-(127.98+3.25)}{30} \tag{11}$$

Wall assembly N:

Intermediate floor junction

$$\Psi = \frac{38.71-26.05}{30} \tag{12}$$

Wall corner junction

$$\Psi = \frac{(47.96)\cdot(2.93+2.93)-(23.77\cdot2.93+23.77\cdot2.93)}{30\cdot(2.93+2.93)} \tag{13}$$

Roof eave junction

$$\Psi = \frac{30.16\cdot(1.41+4.93)-(10.87\cdot1.41+9.78\cdot4.93)}{30\cdot(1.41+4.93)} \tag{14}$$

Window-wall junction

$$\Psi = \frac{138.11-(127.98+2.71)}{30} \tag{15}$$

Wall assembly O:
Intermediate floor junction

$$\Psi = \frac{47.58-36.62}{30} \tag{16}$$

Wall corner junction

$$\Psi = \frac{(64.12)\cdot(2.93+2.93)-(32\cdot2.93+32\cdot2.93)}{30\cdot(2.93+2.93)} \tag{17}$$

Roof eave junction

$$\Psi = \frac{34.39\cdot(1.41+4.93)-(15.37\cdot1.41+9.78\cdot4.93)}{30\cdot(1.41+4.93)} \tag{18}$$

Window-wall junction

$$\Psi = \frac{138.71-(127.98+3.78)}{31} \tag{19}$$

Table 27: Results of the hand calculations

Junction Type	**Assembly H Ψ-value [W/m·K]**	**Assembly N Ψ-value [W/m·K]**	**Assembly O Ψ-value [W/m·K]**
Intermediate Floor	0.36	0.42	0.37
Wall Corner (Exterior)	0.99	0.81	1.09
Roof Eave	0.73	0.12	0.78
Window-Wall	0.24	0.25	0.23

As mentioned earlier, the Ψ-values for the junctions which were not simulated in this study were set as typical in the simulation software. The exterior wall-interior wall junction, the exterior door perimeter junction, the exterior slab-exterior walls junction and exterior slab-interior walls junction were all set as typical, which had the Ψ-values 0.03, 0.03, 0.14, and 0.03 W/m·K respectively. In contrast with the other junctions, the Ψ-values for the roof-interior walls junction was set as good, with a value of 0.01 W/m·K. As this junction contained a thick layer of exterior insulation in connection with the roof construction. In addition to setting the roof-interior walls junction as good, the balcony floor-exterior walls junction was set to 0 W/m·K, as the building did not have any balconies.

6.3 Energy simulations

The present chapter presents the results of the energy simulations carried out in this study. As mentioned in section 6, the results of the energy simulation with the current climate data are presented first, followed by the results with the future climate scenarios. Each set of results includes changes for the heating- and cooling demand. As mentioned earlier, due to a lack of compatibility with the data set for the future climate scenarios, IDA ICE was the only software used for simulating the future climate scenarios.

As mentioned in section 6.2, only roof assembly H70 was simulated in HEAT2, however for the energy simulations roof assemblies' D and G were also used. The reason for using roof assemblies' D and G in the energy simulations are related to the culturally heritage protection placed on the buildings. The culturally heritage protection states that major alterations for the design as well as changing of cladding materials may not be carried out. Roof assemblies' D and G were therefore used, as they were relative similar to that of the existing roof constructions. Roof assembly D would replace the roof construction with the copper cladding on the 6th floor, while roof assembly G would replace the roof construction with the bitumen cladding on the 6th floor.

6.3.1 Current climate data

The results for the reference cases for the A-building all showed quite similar results to the given data from Akademiska Hus. This was due to the before mentioned input data calibration, with an annual heating demand of 88 and 91 kWh/m^2 from IDA ICE and Design Builder respectively, while the results from Honeybee showed 85 kWh/m^2, as shown on Figure 142. The results for the modified wall cases showed a similar reduction of the annual heating demand by approximately 20-25%. As for the roof case, a reduction of the annual heating demand by approximately 3-5% was achieved.

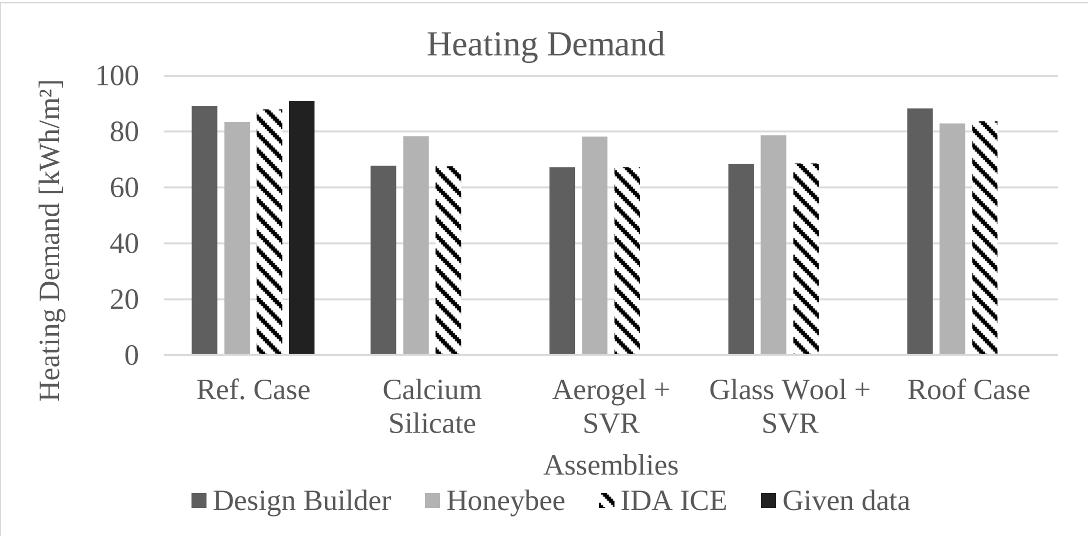


Figure 142: Heating demand for the A-building with current climate data.

Although the same inputs were used for V-building, the results for the reference cases showed that the annual heating demand would be approximately 10-15% lower in comparison to the A-building, as shown in Figure 143. In contrast to the A-building, the V-building showed a slight bigger reduction of the annual heating demand for modified wall cases. The modified wall cases showed a reduction of 25-30%, while the modified roof case showed a reduction of approximately 3%.

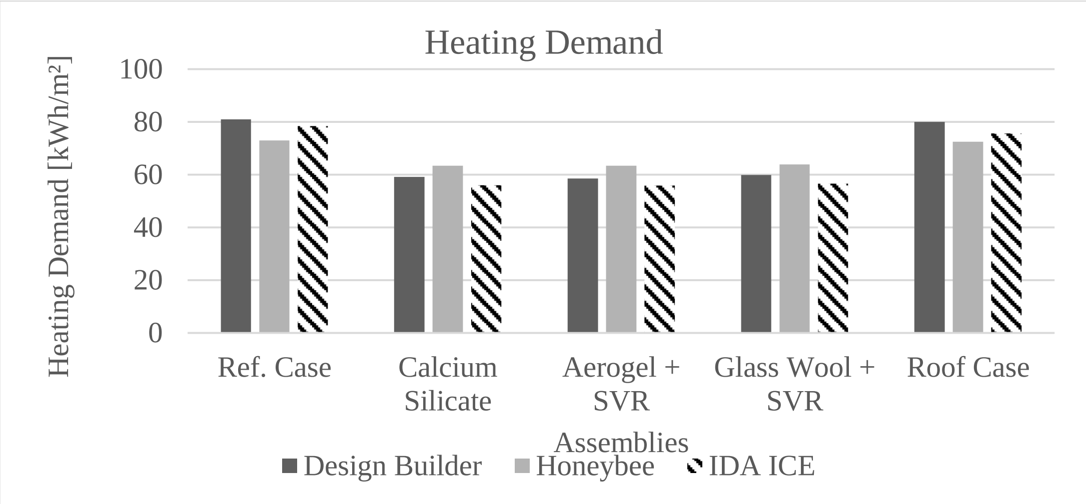


Figure 143: Heating demand for the V-building with current climate data.

As shown on Figure 144-145, the results for the cooling demand for the reference case simulated in Design Builder, Honeybee and IDA ICE, were relatively close to the cooling demand which was provided by Akademiska Hus for the A-building. While the results showed that the V-building showed that Design Builder and Honeybee would experience a cooling around one third of the given value. The cooling demand from IDA ICE was shown to be around 40% higher than the given value from Akademiska Hus for both buildings, while Honeybee was shown to be 50-60% lower than the given value for both buildings. When the reference cases were compared with the modified cases, the results for the A-building showed almost no change in Design Builder and IDA ICE. The only exception was the modified roof case in Design Builder which experienced an increase of approximately 50%. Honeybee on the other hand showed an increase by approximately 60% for all the modified wall cases. The results for the V-building showed only a small increase in the cooling demand between the reference case and the modified wall cases for Design Builder and Honeybee, as well as a 30% increase for the modified roof case in Design Builder. IDA ICE showed almost no change in the cooling demand between the cases.

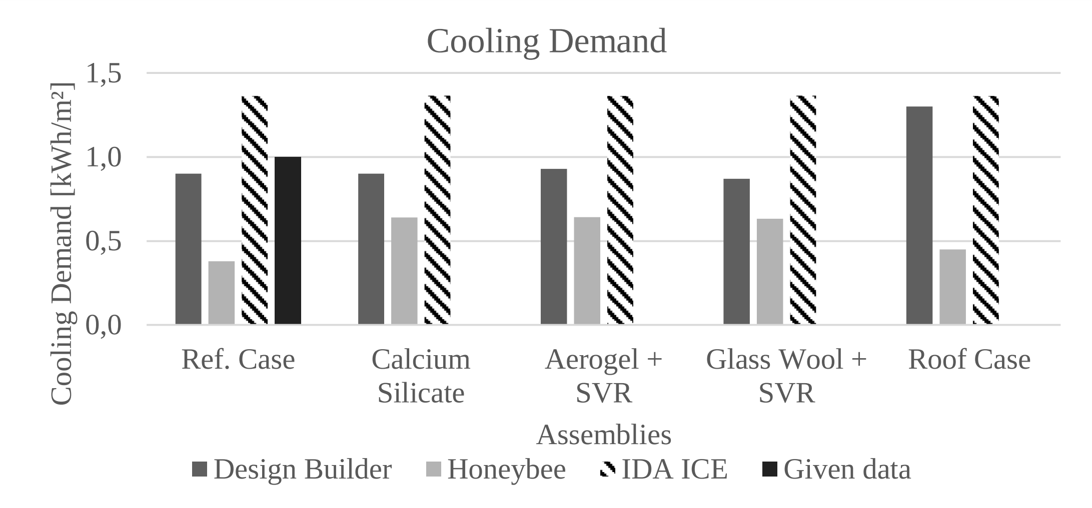


Figure 144: Cooling demand for the A-building with current climate data.

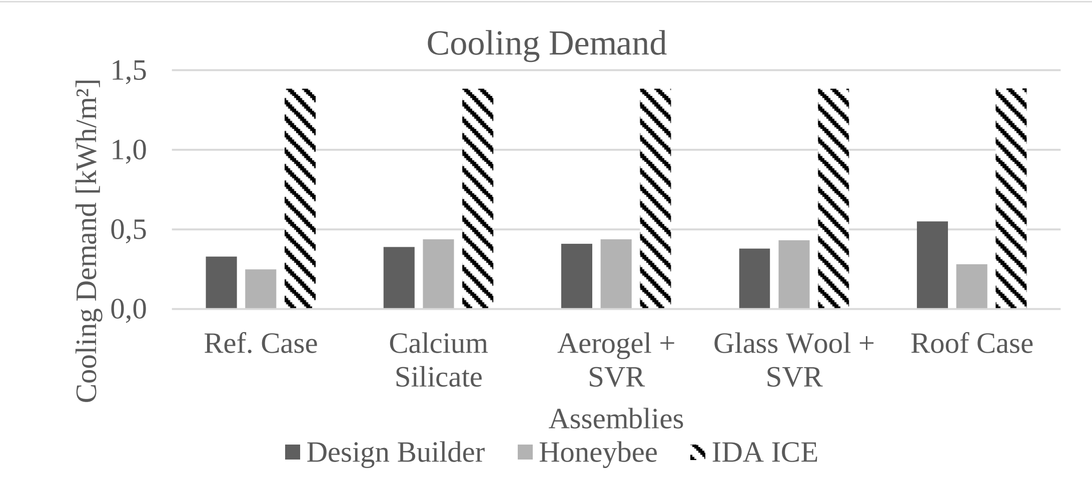


Figure 145: Cooling demand for the V-building with current climate data.

6.3.2 Future climate scenarios

As mentioned in section 5.4, a total of nine future climate scenarios were assessed in the energy performance study. These nine future climate scenarios consisted of the two Global Climate Models IPSL and CNRM, both using the rcp85 greenhouse gas concentration trajectory. In addition, the CNRM climate model also used the rcp45 greenhouse gas concentration trajectory. For each of these three models, three TDY time periods were used, which were 2009-2038, 2039-2068, and 2069-2098. For the assessment of the results, the three future climate scenarios located under each time period were assessed in the same graph. This would show the difference between the IPSL and CNRM Global Climate Models with the rcp85- and rcp45 greenhouse gas concentration trajectory during the same period.

6.3.2.1 Heating demand

The results for the reference case for the A-building showed that the annual heating demand would experience a decrease between the three time periods of approximately 3-8%, as shown in Figure 146-148. With the exception of the RCP45 climate scenarios during the time period 2039-2068, which showed a slight increase of 2-3%. The results for the V-building showed a small increase between the first two time periods of 3-5% with the CNRM RCP45 and IPSL RCP45 climate scenarios. In contrast the CNRM RCP85 climate scenario showed a 5% decrease between the same periods. Between the two last time period the results showed a small decrease of 2-5% for the CNRM RCP45 and IPSL RCP45 climate scenarios. The CNRM RCP85 climate scenario on the other hand showed a slight increase of less than 2%, as shown in Figure 149-151.

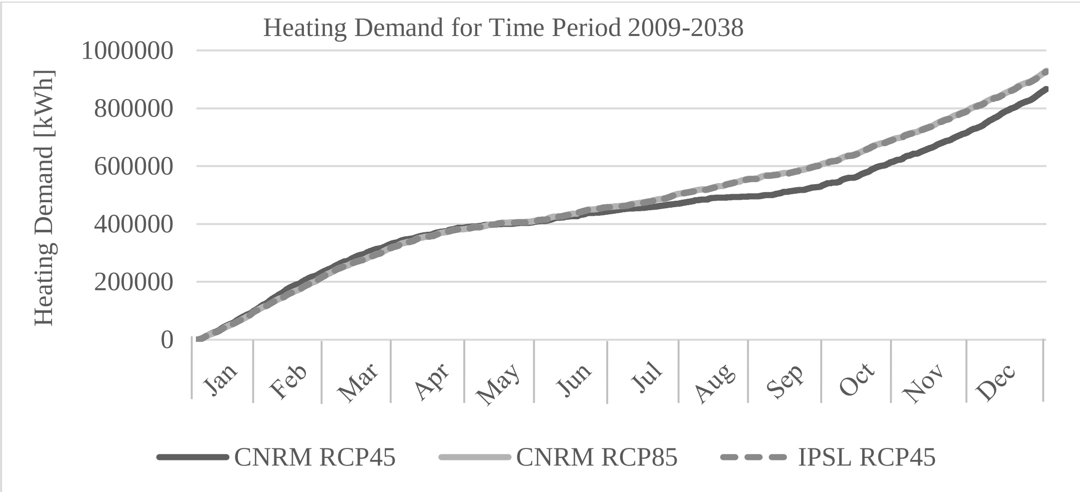


Figure 146: Cumulative heating demand for one year for the reference case in the A-building during the time period 2009-2038, for the city of Lund.

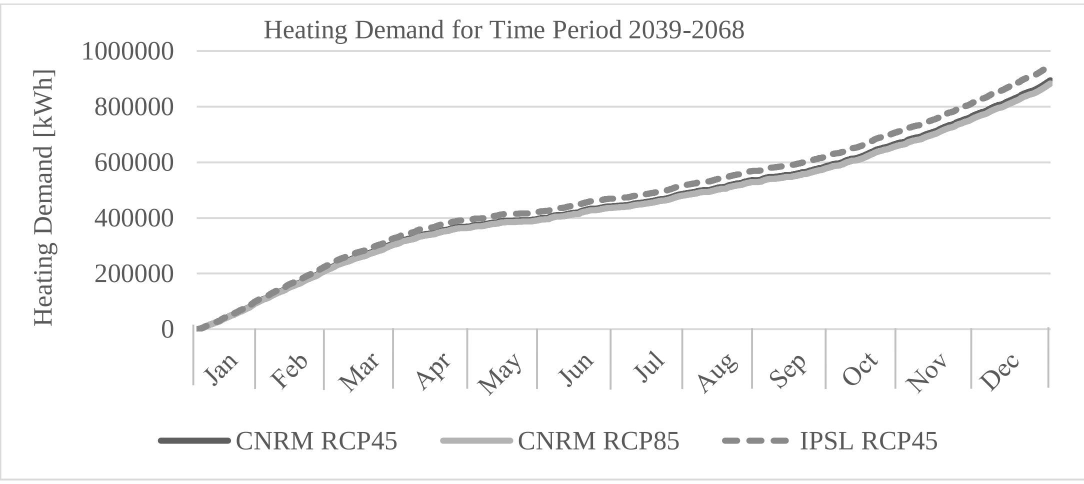


Figure 147: Cumulative heating demand for one year for the reference case in the A-building during the time period 2039-2068, for the city of Lund.

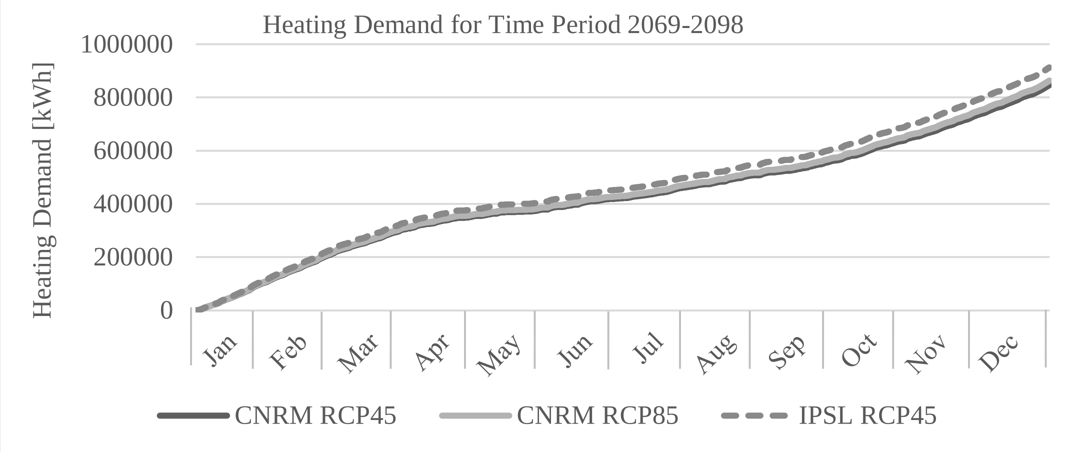


Figure 148: Cumulative heating demand for one year for the reference case in the A-building during the time period 2069-2098, for the city of Lund.

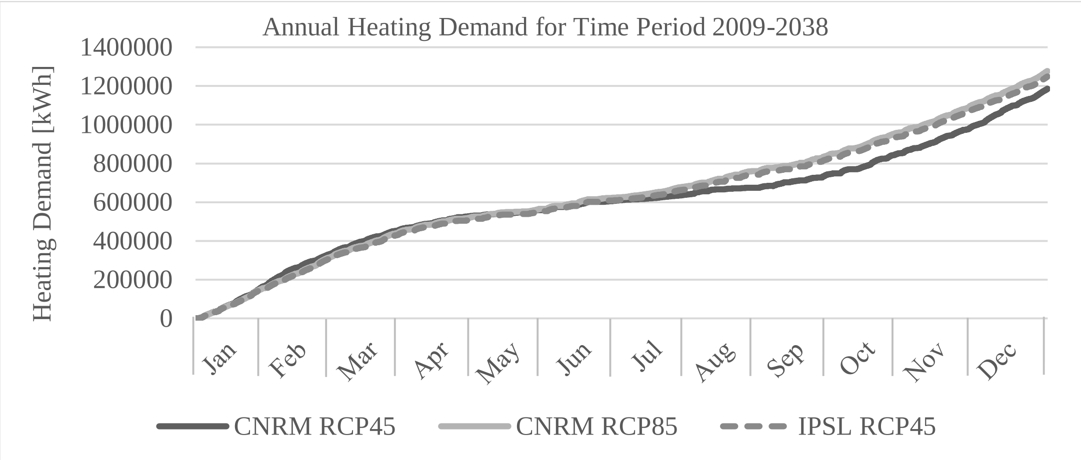


Figure 149: Cumulative heating demand for one year for the reference case in the V-building during the time period 2009-2038, for the city of Lund.

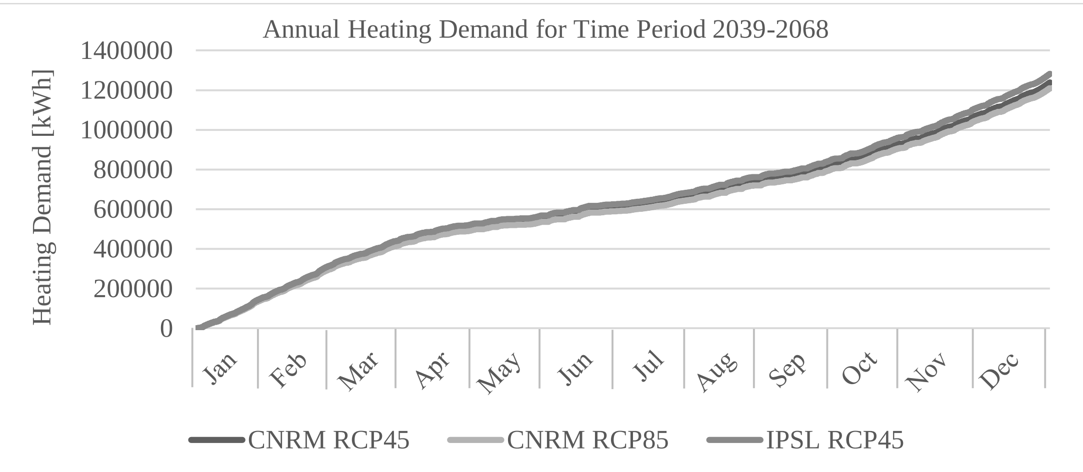


Figure 150: Cumulative heating demand for one year for the reference case in the V-building during the time period 2039-2068, for the city of Lund.

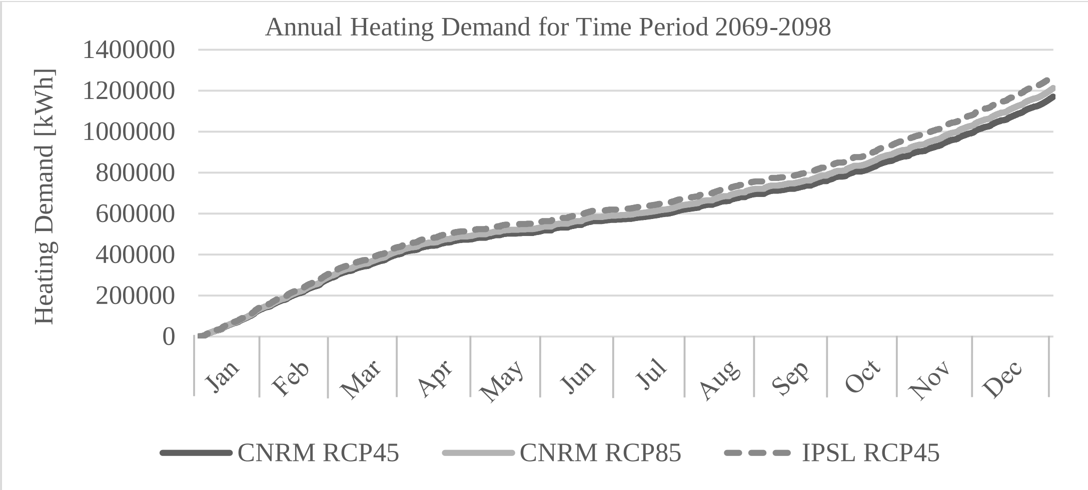


Figure 151: Cumulative heating demand for one year for the reference case in the V-building during the time period 2069-2098, for the city of Lund.

The three wall cases all showed a decrease in the annual energy demand of approximately 20-25% for the A-building, and approximately 30% for the V-building, in comparison to the reference cases, as shown in Figure 152-157. Compared to the reference cases, the trend of the heating curves showed only little difference for the two buildings. When the individual wall cases were compared for both buildings, the results showed a similar trend of the heating curves between wall case N and O to that of the reference case. Where all three climate scenarios showed a relatively similar trend. The results for wall case H on the other hand showed a slight difference in the curve trend between the three time periods, as shown in Figure 146-151 and Figure 152-157. The results for the roof cases showed a decrease in the annual energy demand of approximately 4-5% for both buildings, see Appendix P-Q.

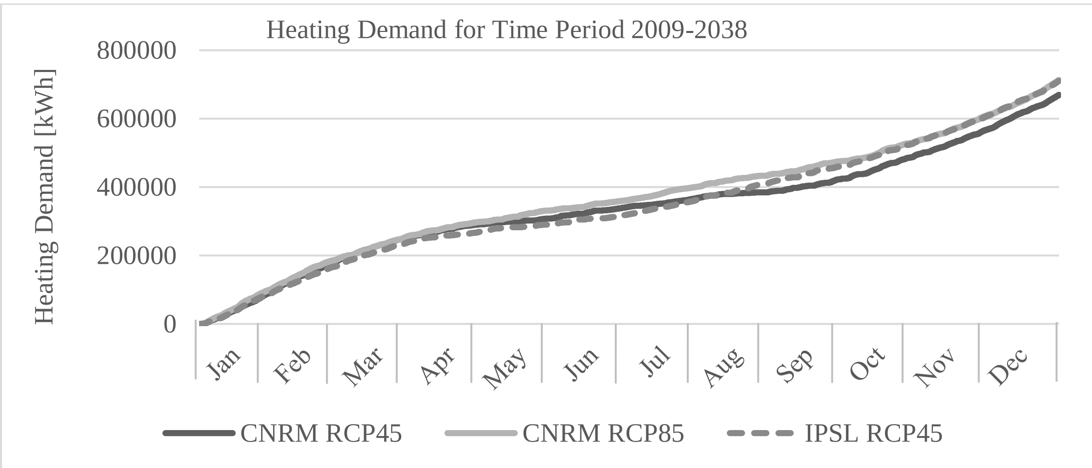


Figure 152: Cumulative heating demand for one year for the wall case H in the A-building during the time period 2009-2038, for the city of Lund.

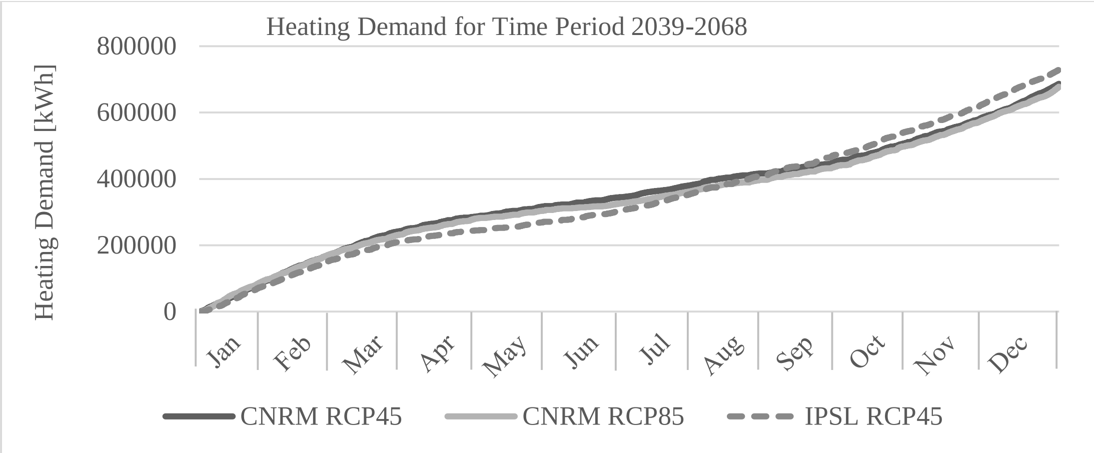


Figure 153: Cumulative heating demand for one year for the wall case H in the A-building during the time period 2039-2068, for the city of Lund.

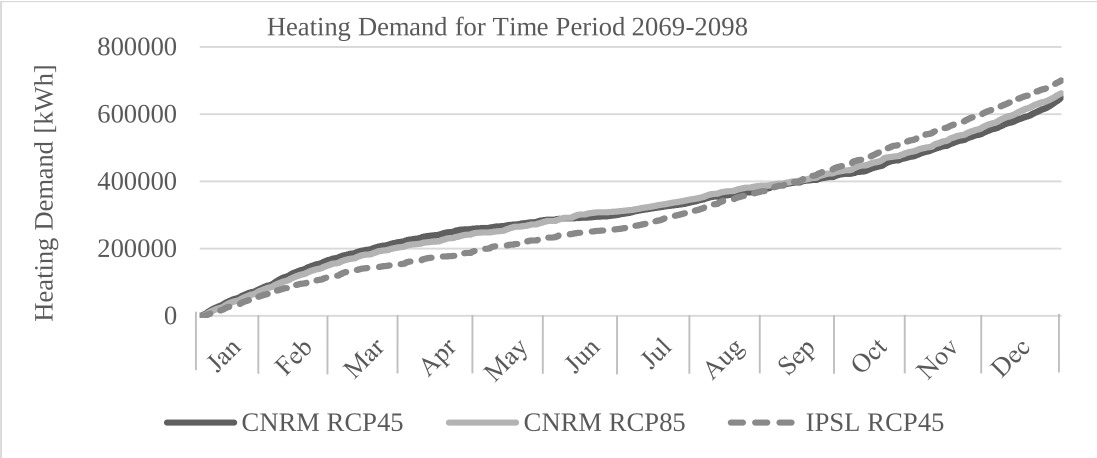


Figure 154: Cumulative heating demand for one year for the wall case H in the A-building during the time period 2069-2098, for the city of Lund.

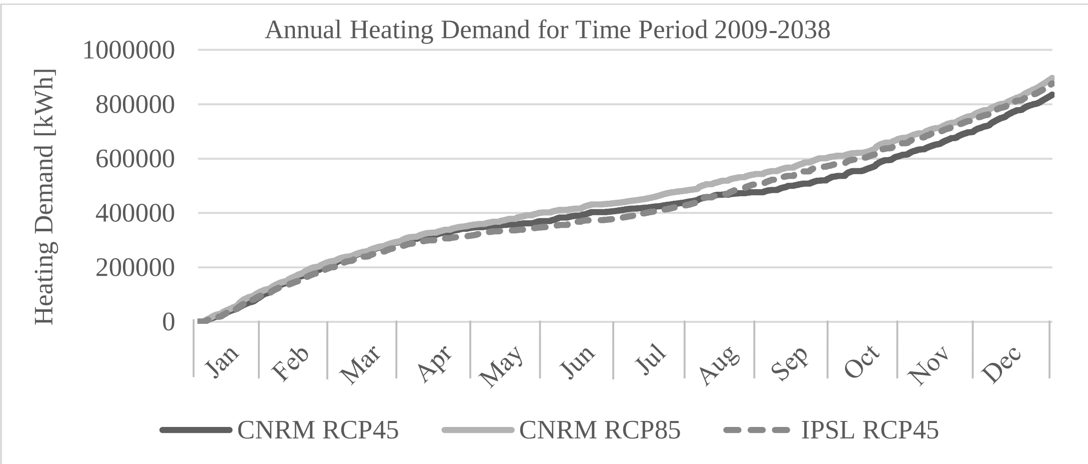


Figure 155: Cumulative heating demand for one year for the wall case H in the V-building during the time period 2009-2038, for the city of Lund.

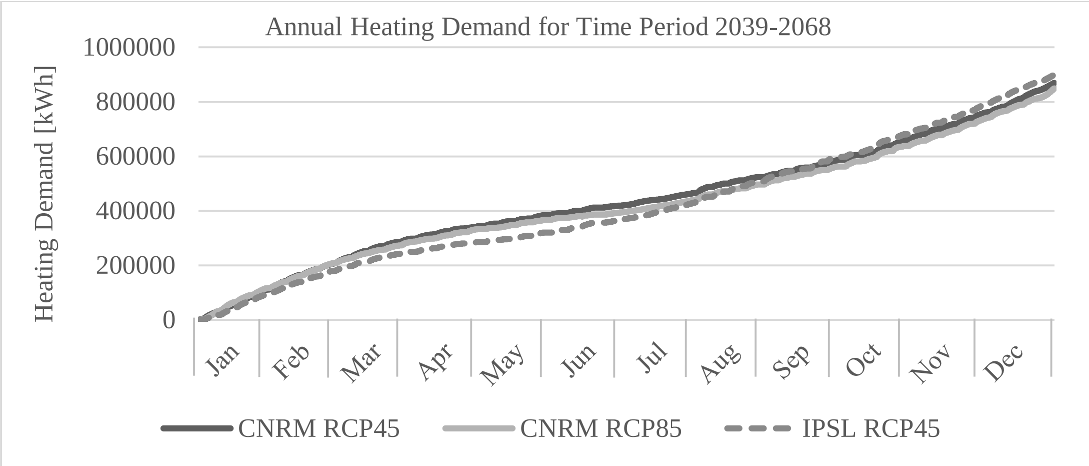


Figure 156: Cumulative heating demand for one year for the wall case H in the V-building during the time period 2039-2068, for the city of Lund.

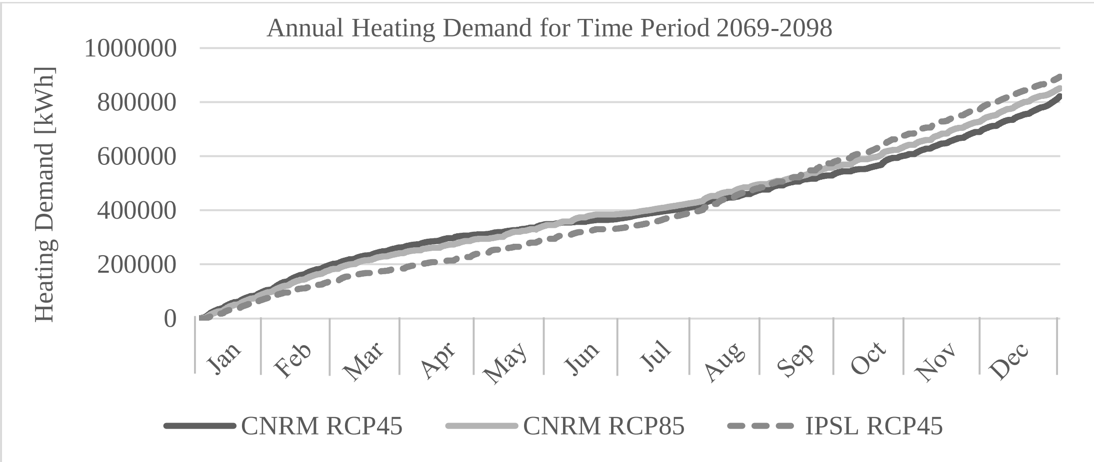


Figure 157: Cumulative heating demand for one year for the wall case H in the V-building during the time period 2069-2098, for the city of Lund.

Table 28 show the annual heating demand per unit area for all the cases for both the A- and V-building. From where it is easy to see the similarity between the results for the three wall cases as well as the before mentioned decrease for the roof cases for the A- and V-building of 4-5%. This showed to be similar for all the roof cases.

Table 28: Heating demand per unit area with future climate scenarios for Lund.

	Annual heating demand [kWh/m^2]									
	V-building					A-building				
	Ref. Case	Wall H	Wall N	Wall O	Roof Case	Ref. Case	Wall H	Wall N	Wall O	Roof Case
CNRM_rcp45_2009_2038	64	46	46	47	62	71	55	55	56	67
CNRM_rcp45_2039_2068	67	48	48	48	65	74	57	56	58	70
CNRM_rcp45_2069_2098	64	46	45	46	61	70	54	53	54	67
CNRM_rcp85_2009_2038	69	49	49	50	67	76	59	58	59	73
CNRM_rcp85_2039_2068	66	47	47	47	63	72	55	55	56	69
CNRM_rcp85_2069_2098	66	47	47	48	63	71	54	54	55	67
IPSL_rcp85_2009_2038	67	48	48	49	65	76	58	58	59	72
IPSL_rcp85_2039_2068	70	50	50	50	67	78	60	59	61	74
IPSL_rcp85_2069_2098	69	49	49	50	66	75	58	58	59	72

6.3.2.2 Cooling demand

As seen for the energy simulations with the current climate data, the results for the two buildings showed very little change in the cooling demand between the different cases. The only major changes occurred between the different future climate scenarios, as shown in Figure 158-163. The two buildings showed an almost identical trend for the cooling demand curve as well as a similar percentage in the increase of the annual cooling demand. Looking at the changes between the different future climate scenarios, showed an increase in the cooling demand occurring between the different time periods. An increase of 15-68% was noticed between the first two time periods, as shown in Figure 158-159 and Figure 161-162. Between the two last time periods an increase of 45-50% was noticed for the CNRM RCP85 and IPSL RCP45 climate scenarios. The CNRM RCP45 climate scenario on the other hand showed only a small increase of approximately 1-2%. This change between the time periods were very similar between the different cases.

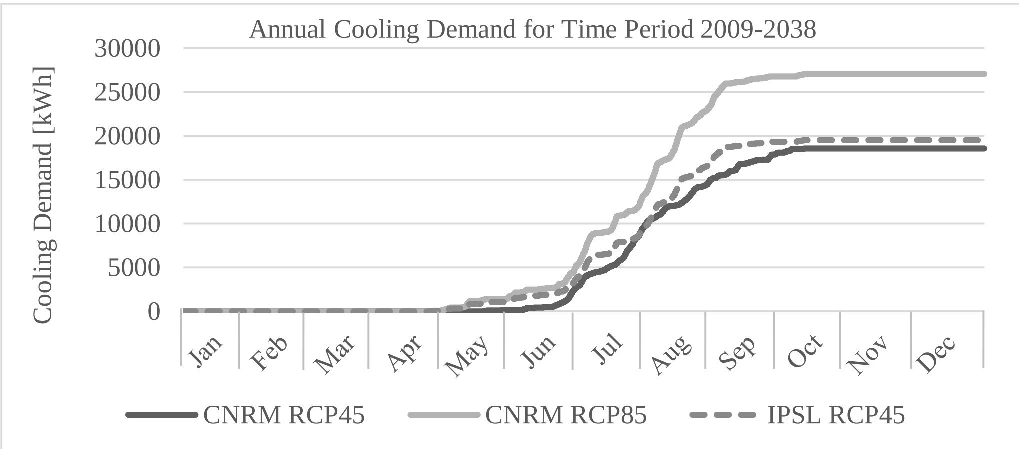


Figure 158: Cumulative cooling demand for one year for the reference case in the A-building during the time period 2009-2038, for the city of Lund.

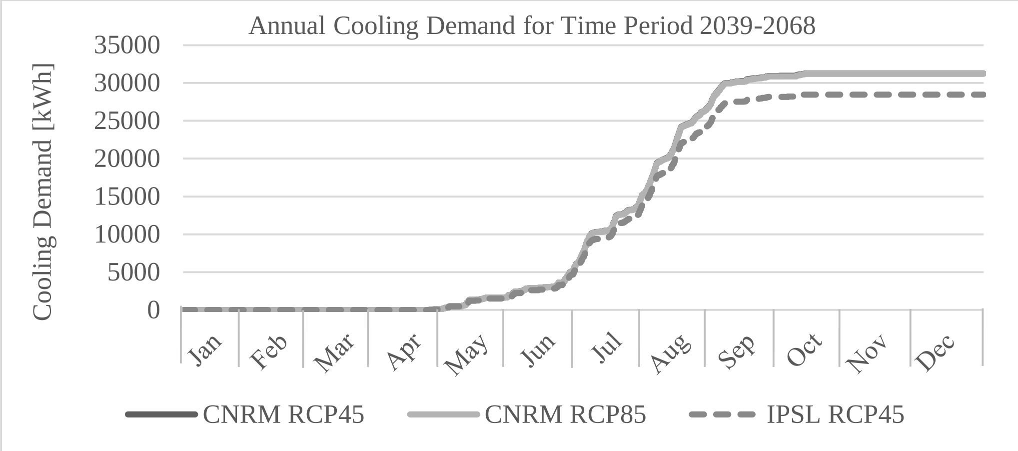


Figure 159: Cumulative cooling demand for one year for the reference case in the A-building during the time period 2039-2068, for the city of Lund.

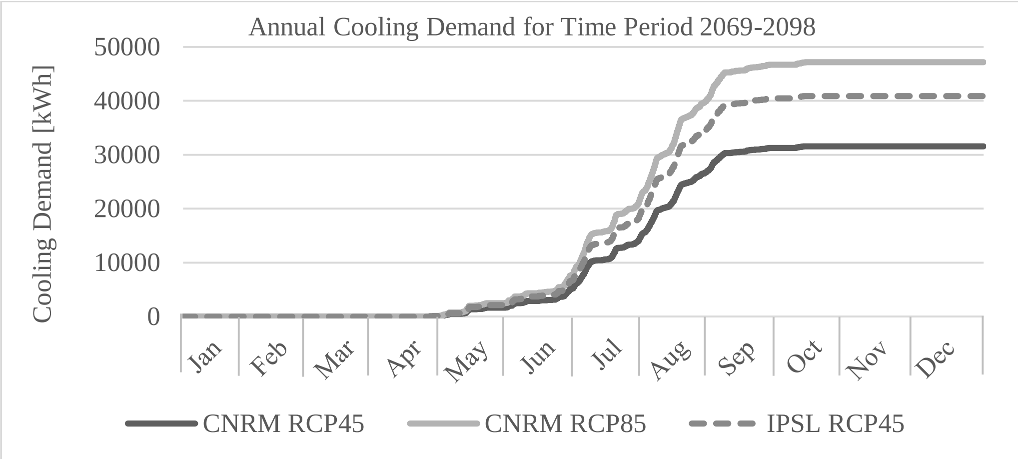


Figure 160: Cumulative cooling demand for one year for the reference case in the A-building during the time period 2069-2098, for the city of Lund.

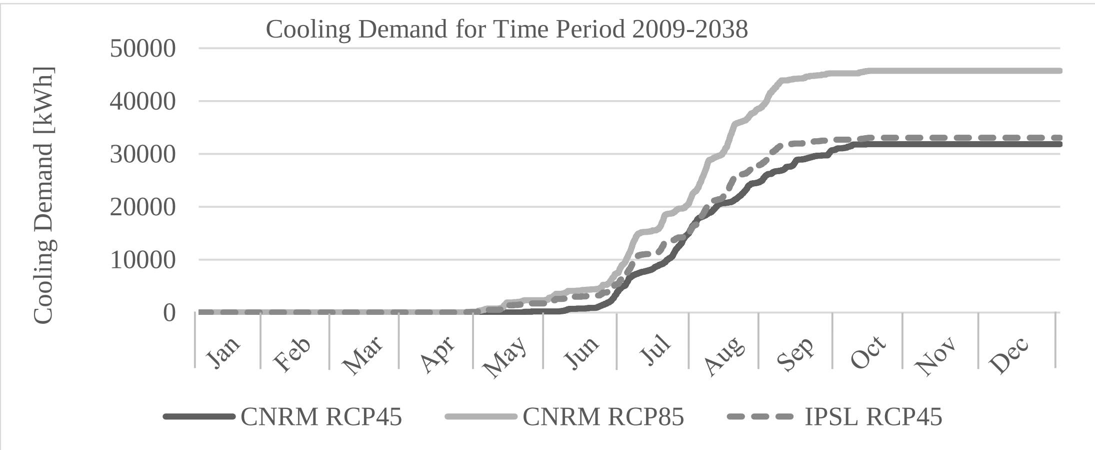


Figure 161: Cumulative cooling demand for one year for the reference case in the V-building during the time period 2009-2038, for the city of Lund.

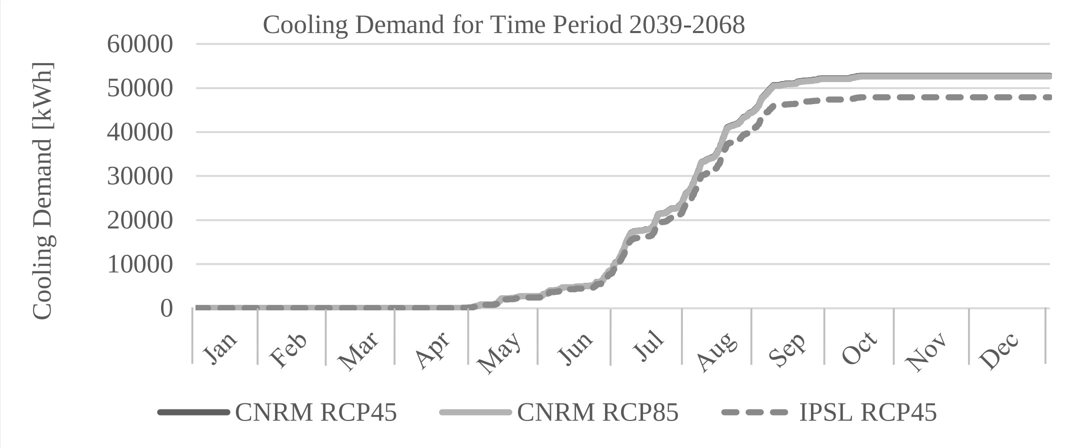


Figure 162: Cumulative cooling demand for one year for the reference case in the V-building during the time period 2039-2068, for the city of Lund.

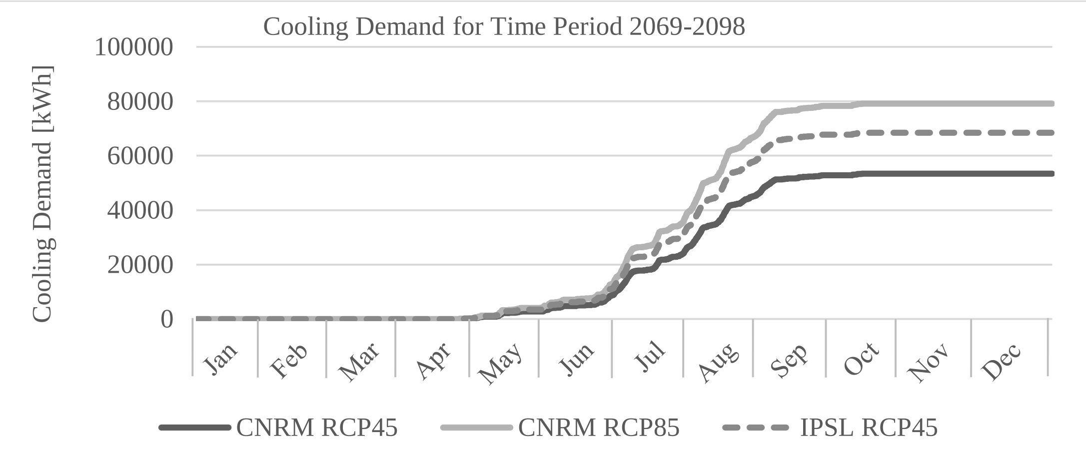


Figure 163: Cumulative cooling demand for one year for the reference case in the V-building during the time period 2069-2098, for the city of Lund.

Table 29 show the annual cooling demand per unit area for all the cases for both the A- and V-building. From where it is easy to see the cooling demand does not change a lot between the different cases, only between the future climate scenarios. The increase of the annual cooling demand between the future climate scenarios are also visible here in the table. The results shown in the table suggest an increase of the annual cooling demand occurring between the three time periods for all the cases.

Table 29: Cooling demand per unit area with future climate scenarios for Lund.

	Annual cooling demand [kWh/m^2]									
	V-building					A-building				
	Ref. Case	Wall H	Wall N	Wall O	Roof Case	Ref. Case	Wall H	Wall N	Wall O	Roof Case
CNRM_rcp45_2009_2038	1.41	1.42	1.42	1.42	1.41	1.37	1.38	1.38	1.38	1.37
CNRM_rcp45_2039_2068	2.33	2.33	2.33	2.33	2.33	2.30	2.30	2.30	2.31	2.30
CNRM_rcp45_2069_2098	2.36	2.35	2.36	2.36	2.36	2.33	2.33	2.33	2.33	2.33
CNRM_rcp85_2009_2038	2.02	2.02	2.02	2.02	2.02	1.99	2.00	2.00	2.00	2.00
CNRM_rcp85_2039_2068	2.32	2.32	2.32	2.32	2.32	2.30	2.30	2.30	2.30	2.30
CNRM_rcp85_2069_2098	3.50	3.50	3.50	3.50	3.50	3.48	3.48	3.48	3.48	3.48
IPSL_rcp85_2009_2038	1.46	1.46	1.46	1.46	1.46	1.44	1.44	1.44	1.44	1.44
IPSL_rcp85_2039_2068	2.11	2.11	2.11	2.11	2.12	2.10	2.10	2.10	2.10	2.10
IPSL_rcp85_2069_2098	3.02	3.02	3.02	3.02	3.03	3.01	3.02	3.02	3.02	3.02

6.4 Life cycle cost

The life cycle cost was conducted after the energy simulations for the A- and V-building were completed. The LCC calculations were carried out as described in section 5.8, with the given materials, quantities, machinery, costs, and task durations as stated in Appendix L-M. The LCC was conducted for six cases for each of the two buildings, the reference wall case, the reference roof case, the three modified wall cases (wall assemblies H, N, and O), and the one modified roof case including roof assemblies D, G, and H70. In the same way as for the energy simulations, the three roof assemblies were applied to their respective locations, and combined into one case, as described in section 6.3.

The results from the LCC showed no economic background for renovating neither the wall or roof constructions of any of the two buildings. As the construction-, maintenance- and space loss costs were considerably higher than the energy saving potential of the retrofitting measures, as shown in Figure 164-165 below. The costs of the operational energy for space heating, showed to be the main contributor within the LCC, accounting for approximately 40-50% of the total costs for the modified wall, approximately 65% roof cases, while approximately 90-95% for reference cases. The second highest contributor was the initial costs, which accounted for approximately 30-40% of the total costs for the modified wall and roof cases.

Comparing the three wall assemblies H, N, and O, showed only a marginal difference for the costs of the operational energy for space heating. In contrast to the cost for space heating, a large difference was noticed for the initial costs. Where both the calcium silicate assembly and aerogel assembly (models H and N) showed to be considerably more expensive in comparison to the smart vapour retarder assembly (model O). The large difference between the initial costs of the three wall showed to be related to the large price difference between the calcium silicate- and aerogel insulation, in comparison to the glass wool insulation used for the smart vapour retarder assembly. As an example, the material price for the glass wool insulation used for the LCC of the V-building had a total price of approximately 210000 SEK, while the calcium silicate- and aerogel insulation had a total price of approximately 4500000 and 6000000 SEK respectively. In addition to the initial costs, the calcium silicate assembly also showed a higher cost for space loss in comparison with the two other assemblies.

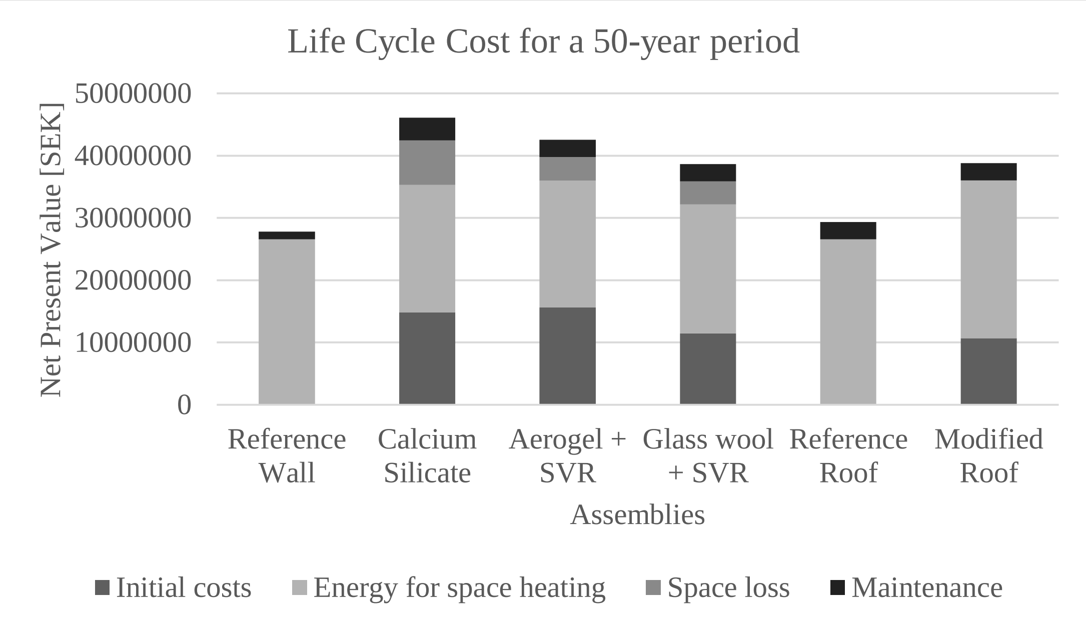


Figure 164: Life cycle cost for the A-building

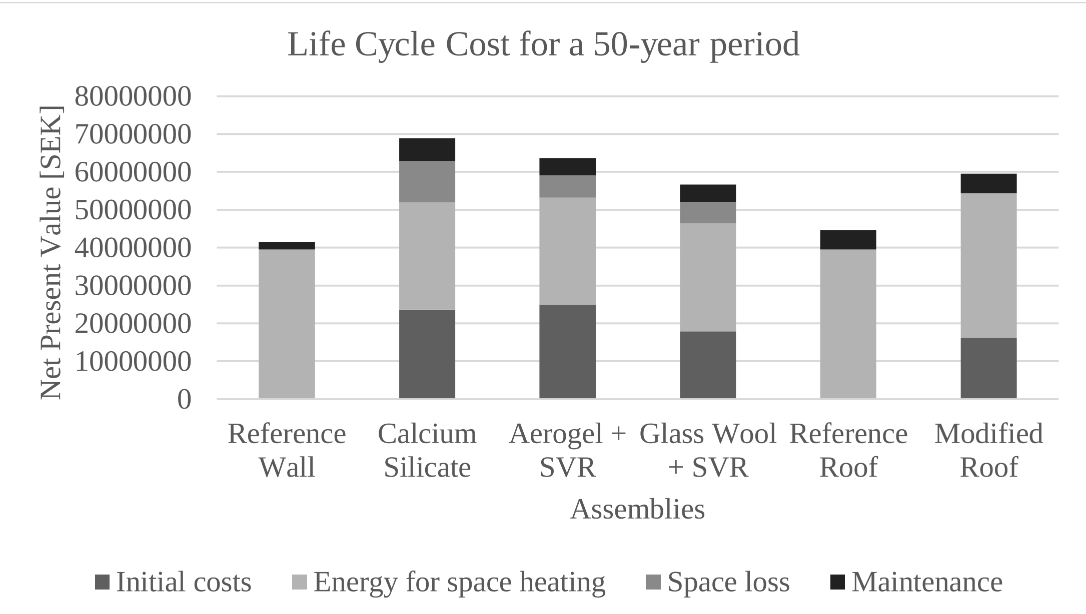


Figure 165: Life cycle cost for the V-building

In the same way as for the energy demand for space heating in section 6.3.1 and 6.3.2, the LCC costs were calculated per unit floor area. This made a valid comparison between the LCC calculations for the two buildings possible, as shown in Figure 166-167 below. The results showed that the retrofitting measures had a price ranging from approximately 2100 SEK/m^2 to approximately 3400 SEK/m^2 for the A-building, while from approximately 1800 SEK/m^2 to approximately 3000 SEK/m^2 for the V-building. With the reference wall case being the least expensive case and the Wall assembly H case to be the most expensive. This was common for both buildings. When the prices for the retrofitting measures for the two buildings were compared, the results showed the retrofitting measures to be slightly more expensive for the A-building than for the V-building. The price difference between the cases ranged from approximately 190 SEK/m^2 to 350 SEK/m^2.

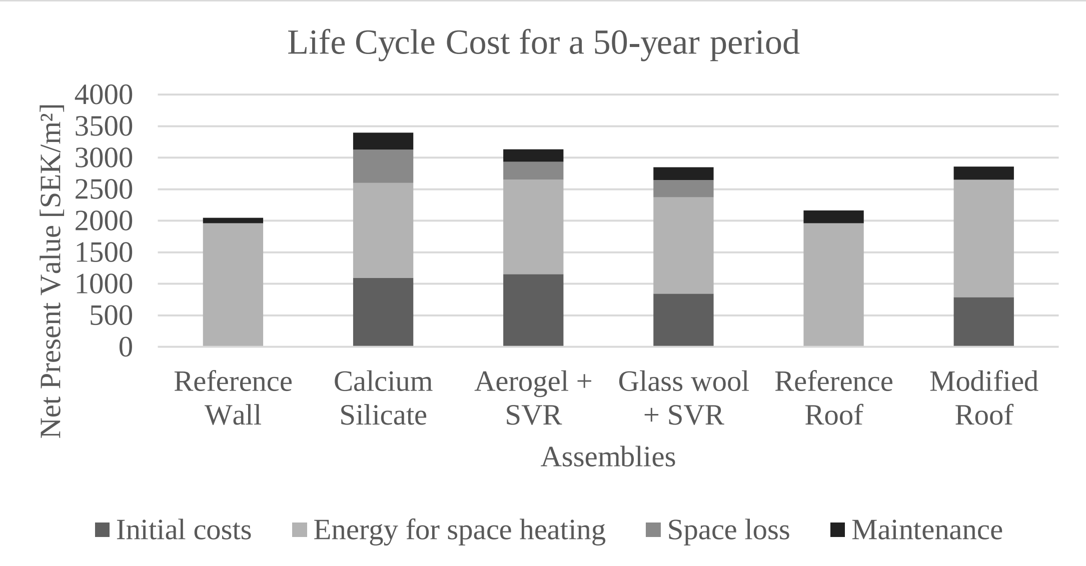


Figure 166: Life cycle cost for the A-building, calculated by unit floor area.

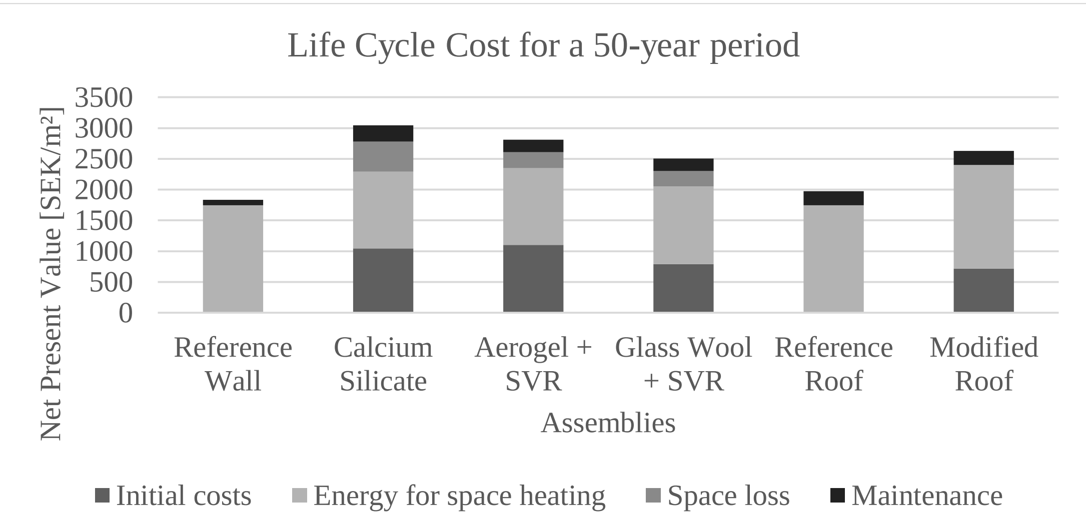


Figure 167: Life cycle cost for the V-building, calculated by unit floor area.

6.5 Life cycle assessment

The present chapter presents the results of the life cycle assessment carried out in this study for the A- and V-building. The results for the individual environmental impact indicators are presented first, followed by the results of the Shadow Cost calculations. As mentioned in section 5.9, the Shadow Cost accounts for all five of the environmental impact indicators.

6.5.1 The environmental impact indicators

As mentioned in section 5.9, the environmental feasibility study addressed five environmental impact indicators. These were Global Warming Potential for 100 years (GWP100), Ozone Depletion Potential (OPD), Photochemical Oxidation Creation Potential (POCP), Acidification Potential (AP), and Eutrophication Potential (EP). And in the same way as for the LCC, the results were calculated per unit floor area, to allow for a valid comparison between the two buildings.

Looking at the global warming potential for 100 years, the results from the LCA showed that the cases for the V-building would be responsible for emitting approximately 140-175 kg CO_2 eq. per m^2 floor area. The cases for the A-building were shown be responsible for emitting approximately 160-195 kg CO_2 eq. per m^2 floor area. The individual cases showed that all three of the modified wall cases to be environmentally feasible. This was common for both buildings, as shown in Figure 168-169. Despite the fact that case O had the highest energy demand for space heating (therefore also the highest environmental impact from space heating) of the three modified wall cases, this case showed the best overall result. This was due to a considerably lower environmental impact from the construction- and maintenance phases as well as the material production, compared with the two other modified wall cases. The modified roof construction on the other hand only showed to be environmentally infeasible for the both buildings. The results suggested that the higher GWP100 for the modified roof construction was due a limited reduction of the energy demand for space heating, which would not offset the environmental impact from constructing the new roof. One reason for the environmental infeasibility of the modified roof constructions occurring, was due to only a small percentage of the existing roof having a poor roof construction worth renovating.

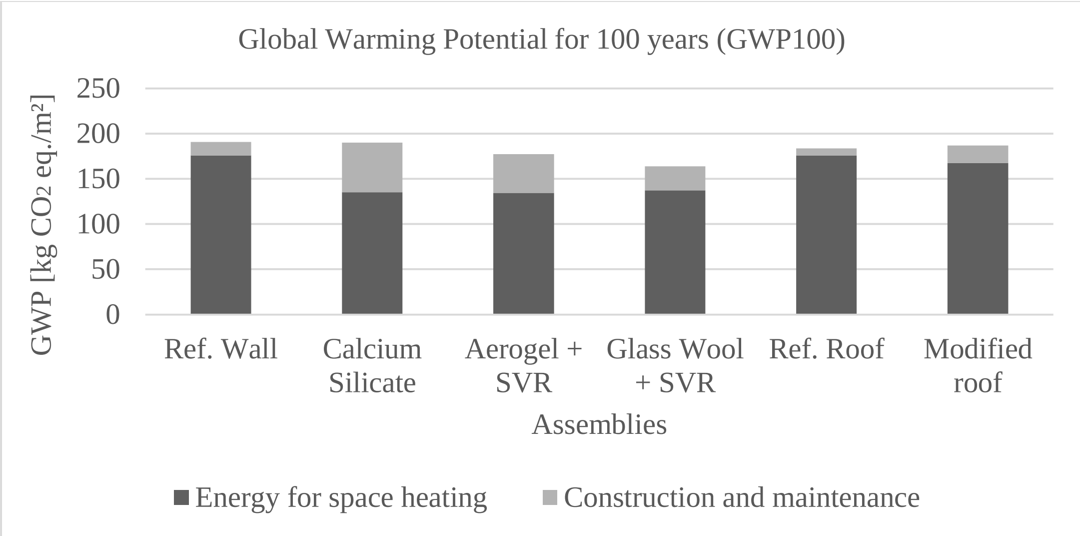


Figure 168: Global warming potential for the A-building, calculated by unit floor area.

As shown in Figure 168-169, the GWP100 emissions for the V-building showed to be lower than for the A-building, by approximately 20-25 kg CO_2 eq. for most of the modified cases. The two reference cases showed to lower for the V-building, by approximately 15-20 kg CO_2 eq. In the same way as for the LCC, the results showed that the higher GWP100 emissions for the modified cases for the A-building was related to the slightly smaller energy saving by the retrofitting measures, in comparison to the V-building.

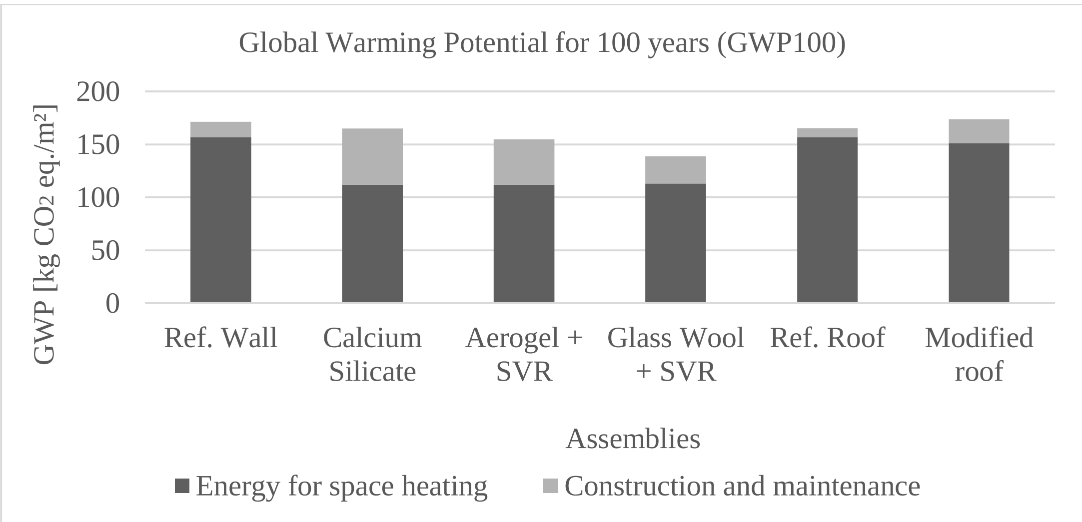


Figure 169: Global warming potential for the V-building, calculated by unit floor area.

Regarding the acidification potential, the results showed environmental feasibility for all the modified cases, for both buildings, as shown in Figure 170-171. The modified wall cases showed a 20-25% reduction in the AP compared with the reference wall, from approximately

1.8-2 kg SO_2 eq. per m^2 floor area to 1.4-1.6 kg SO_2 eq. The modified roof case showed only a small reduction for the V-building, a reduction of approximate 0.05 kg SO_2 eq. per m^2 floor area. In contrast to the V-building, the A-building showed a small increase of approximate 0.05 kg SO_2 eq. per m^2 floor area.

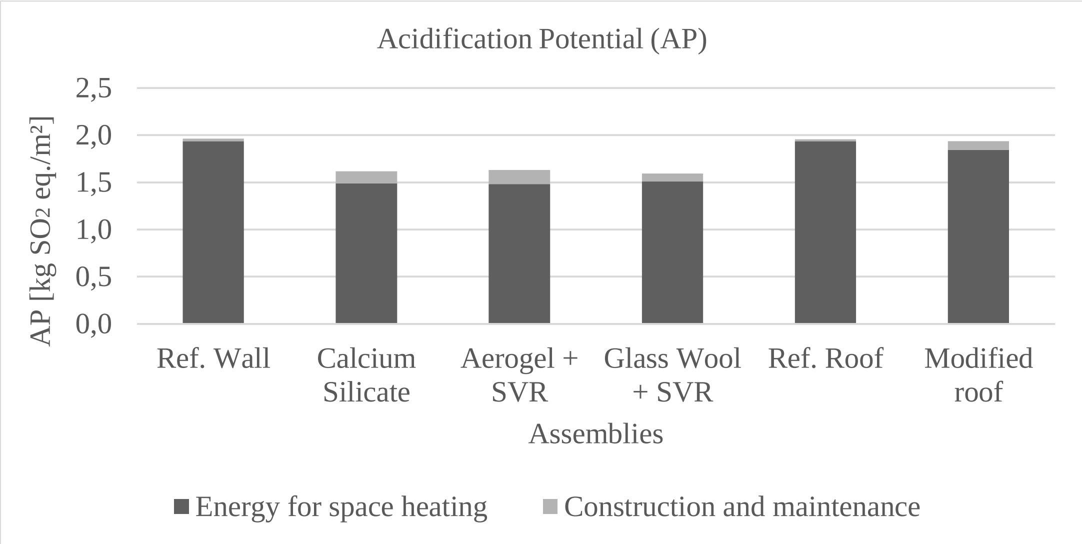


Figure 170: Acidification potential for the A-building, calculated by unit floor area.

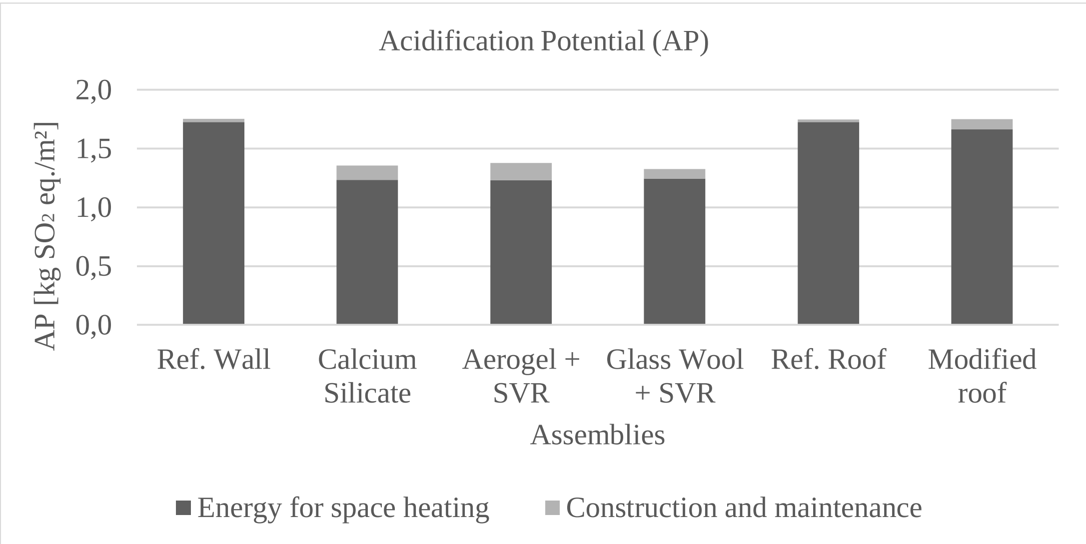


Figure 171: Acidification potential for the V-building, calculated by unit floor area.

The LCA results for the eutrophication potential showed that the all cases would be responsible for emitting approximately 0.25-0.4 kg PO_4 eq. per m^2 floor area, as shown in Figure 172-173. The A-building showed slightly higher emissions that the V-building all the cases. The results for the eutrophication potential showed only a small reduction for the modified roof cases, a reduction of approximate 0.005 kg PO_4 eq. per m^2 floor area. As for the wall cases, the results showed a reduction of approximately 0.07 to 0.08 kg PO_4 eq. per m^2 floor area, a reduction of approximately 20-25%.

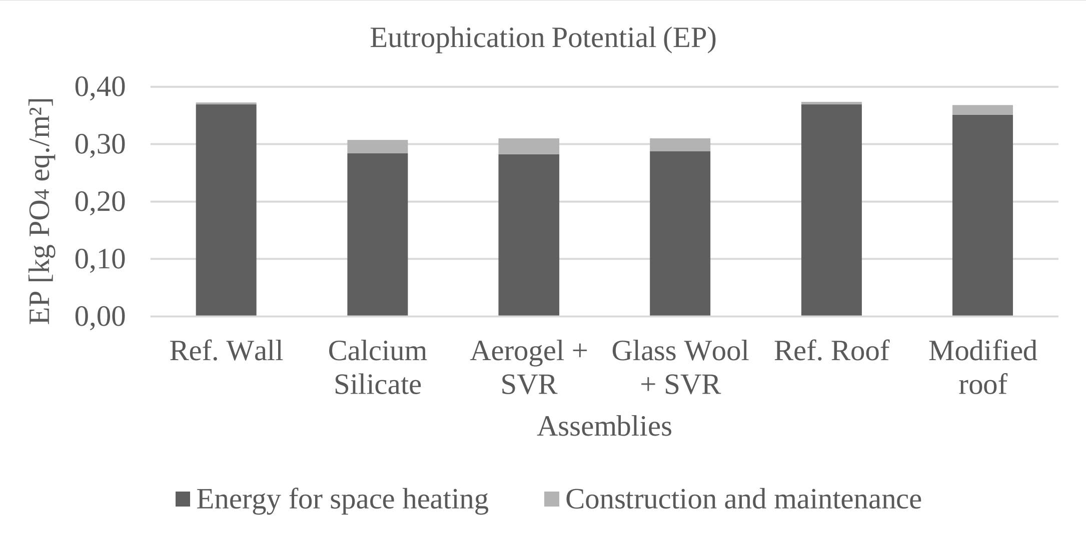


Figure 172: Eutrophication potential for the A-building, calculated by unit floor area.

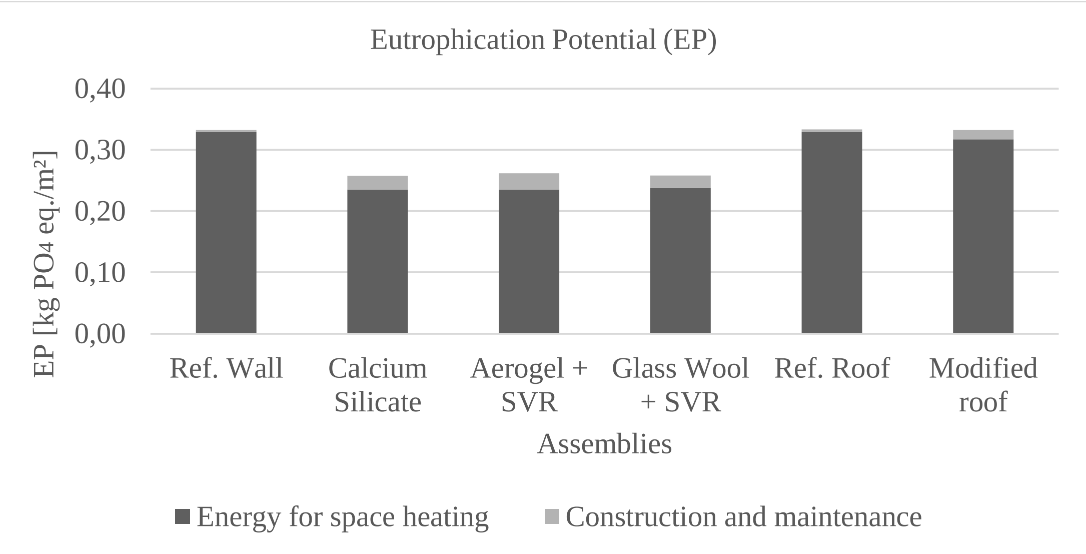


Figure 173: Eutrophication potential for the V-building, calculated by unit floor area.

As seen for the acidification- and eutrophication potential, the results for the ozone depletion potential showed the largest reduction occurring for the modified wall cases, a reduction of approximately 20-25%. Which was a reduction from approximately 0.000020-0.000022 kg CFC-11 eq. per m^2 floor area to approximately 0.000015-0.000017 kg CFC-11 eq., as shown in Figure 174-175. One exception was wall cases N (Aerogel insulation), which showed an environment impact from the construction- and maintenance phases three to four times higher than the other modified wall assemblies. Wall case N only showed a reduction of approximately 5-10%. Which was a reduction from approximately 0.000020-0.000022 kg

CFC-11 eq. per m^2 floor area to approximately 0.000018-0.000021 kg CFC-11 eq. As seen for all the other environmental impact indicators, the modified roof cases showed only a small reduction for the ozone depletion potential, by approximately 5%. Which was a reduction from approximately 0.000022 kg CFC-11 eq. per m^2 floor area to approximately 0.000021 kg CFC-11 eq.

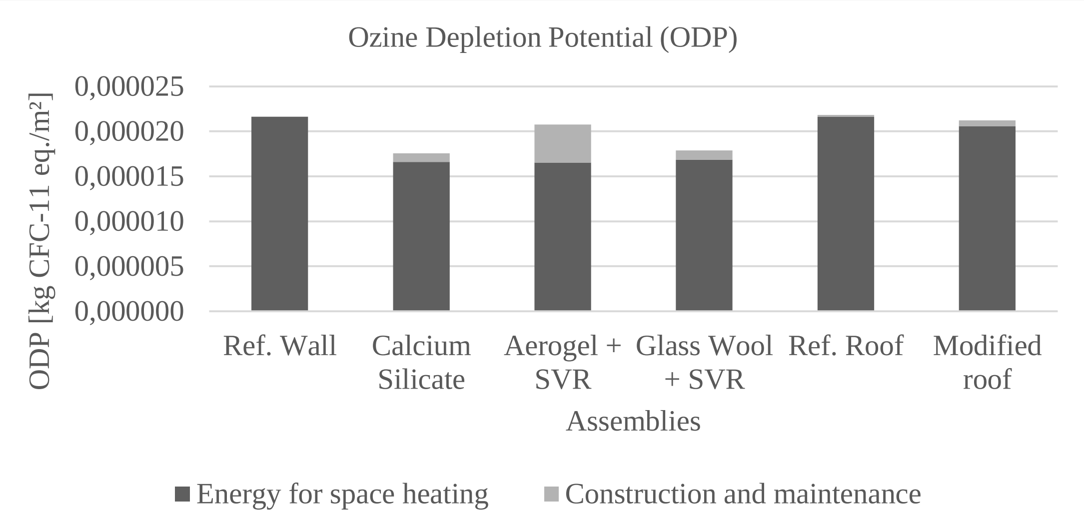


Figure 174: Ozone depletion potential for the A-building, calculated by unit floor area.

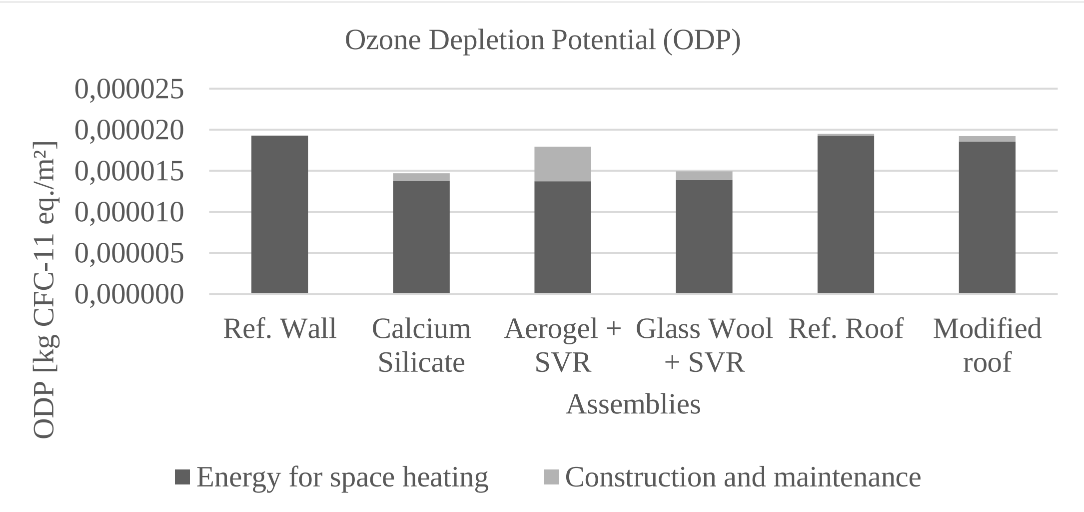


Figure 175: Ozone depletion potential for the V-building, calculated by unit floor area.

As seen for all the other environmental impact indicators, the results for the photochemical oxidation creation potential showed that the modified wall cases would experience the largest reduction, as shown in Figure 176-177. A reduction of approximately 10-20%, from approximately 0.17-0.19 kg C_2H_2 eq. per m^2 floor area to approximately 0.14-0.17 kg C_2H_2 eq. In contrast to all the other environmental impact indicators, the POCP results showed large increase between the existing- and modified roof cases for the buildings. Both buildings showed an increase of approximately 25-30%. Which was an increase from approximately 0.17-19 kg C_2H_2 eq. per m^2 floor area to approximately 0.22-24 kg C_2H_2 eq.

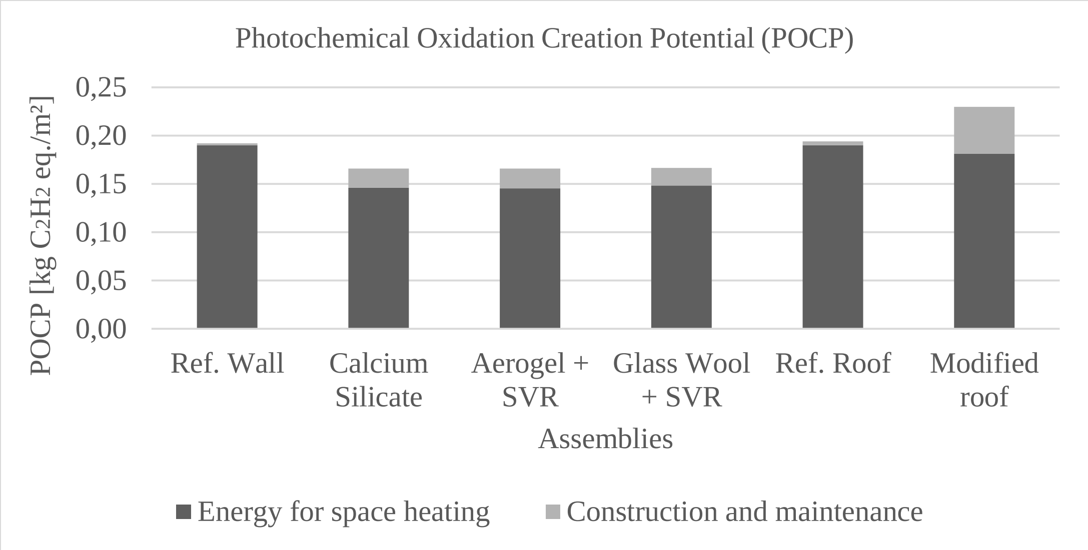


Figure 176: Photochemical oxidant creation potential for the A-building, calculated by unit floor area.

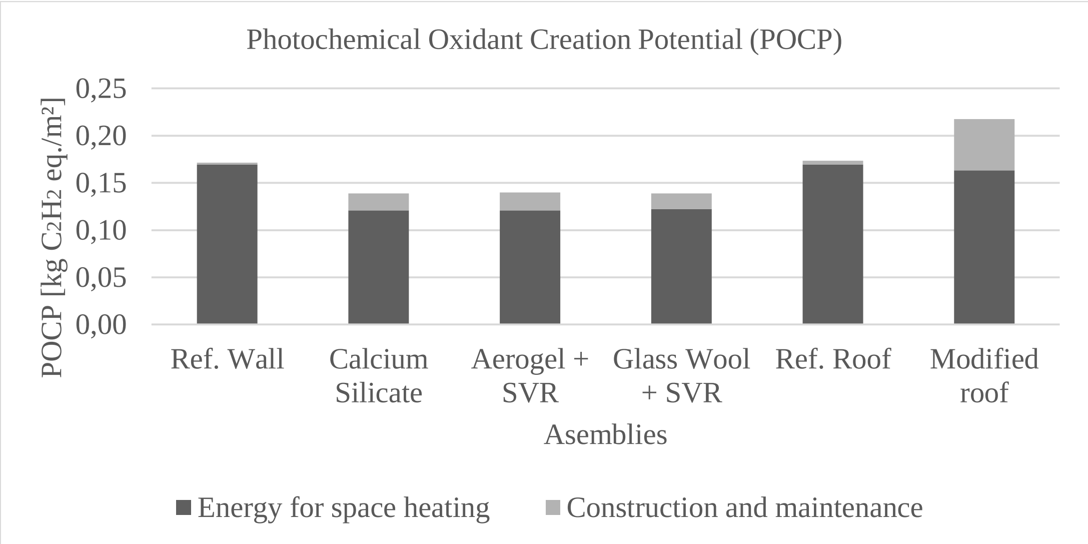


Figure 177: Photochemical oxidant creation potential for the V-building, calculated by unit floor area.

6.5.2 The Shadow Cost

As mentioned in section 5.9, the Shadow Cost method was used to create an easy-understandable comparison between the LCA cases, while accounting for all five of the before mentioned environmental impact indicators. The results of the Shadow Cost calculation for the A-building showed the two reference cases would result in the highest shadow cost of approximately 2.7 million SEK during the 50-year period from the LCA. Wall case O resulted in the lowest shadow cost of approximately 2.2 million SEK, which was a reduction of approximately 19%, as shown in Figure 178. The results from the V-building showed the two reference cases as well as the modified roof case would result in the highest shadow cost of approximately 4 million SEK. As seen for the A-building, wall case O showed the lowest shadow cost of approximately 3.2 million SEK, which was a reduction of approximately 20%, as shown in Figure 179. Both modified roof cases showed to be environmentally infeasible in comparison to the reference roof cases, by approximately 5000-10000 SEK. Looking deeper into the shadow cost results for the three wall cases showed the environmental impact caused by the energy demand for space heating to be almost identical for the three cases. The main difference between the cases was due to the construction- and maintenance phases as well as material production.

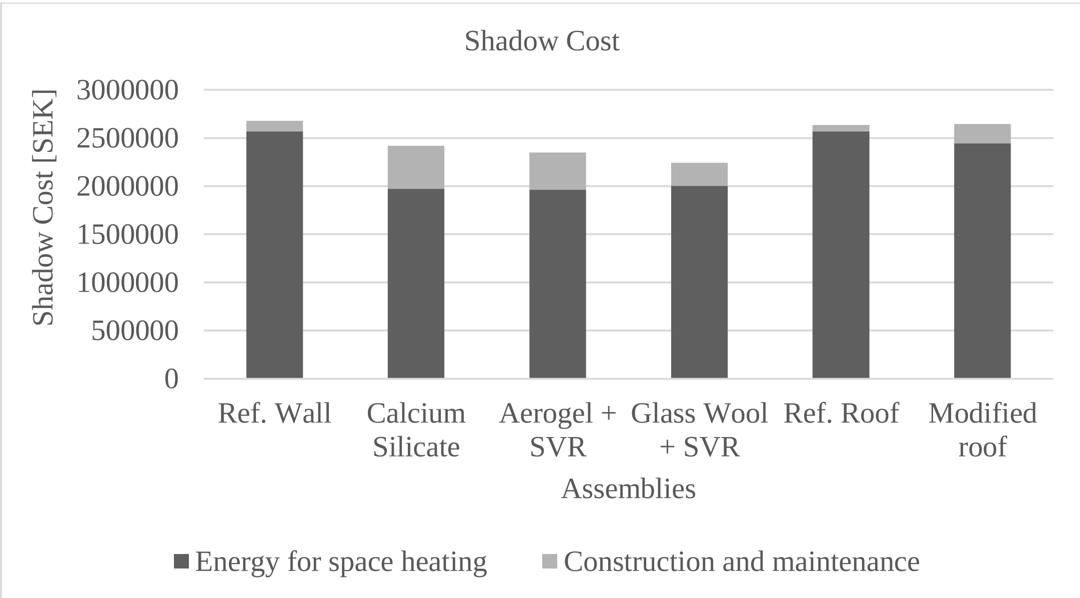


Figure 178: Shadow Cost for the A-building.

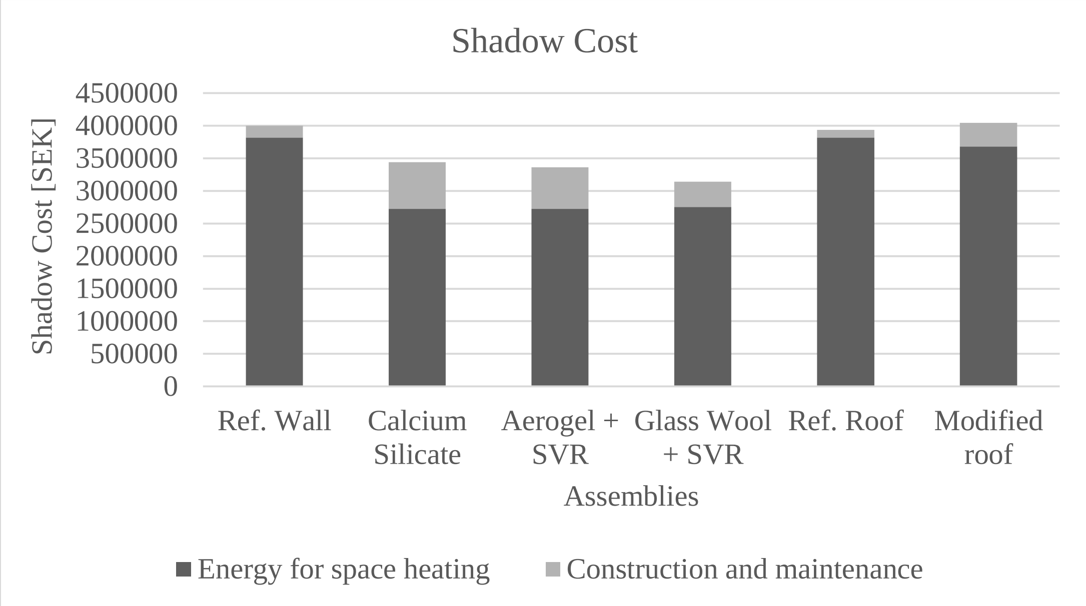


Figure 179: Shadow Cost for the V-building.

In the same way as for the LCC results, the Shadow Cost results were calculated by unit floor area for a valid comparison between the two buildings. The shadow cost showed that the cases would result in a shadow cost of approximately 140-200 SEK per m^2 floor area, as shown in Figure 180-181. When compared, the results for the A-building was shown to be slightly higher for all the cases than the V-building, a difference of 15-25 SEK per m^2 between the different cases.

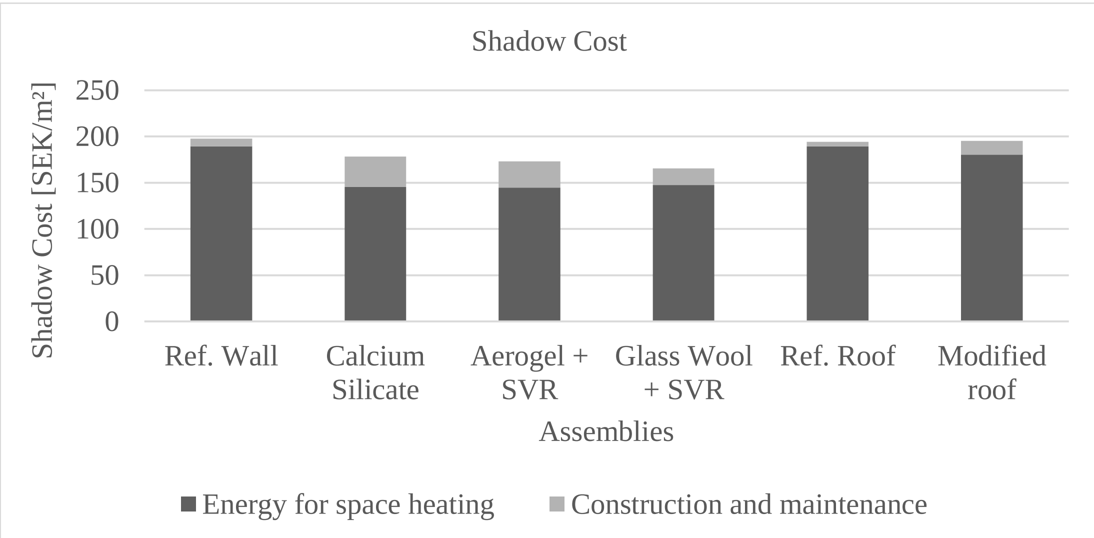


Figure 180: Shadow Cost for the A-building, calculated by unit floor area.

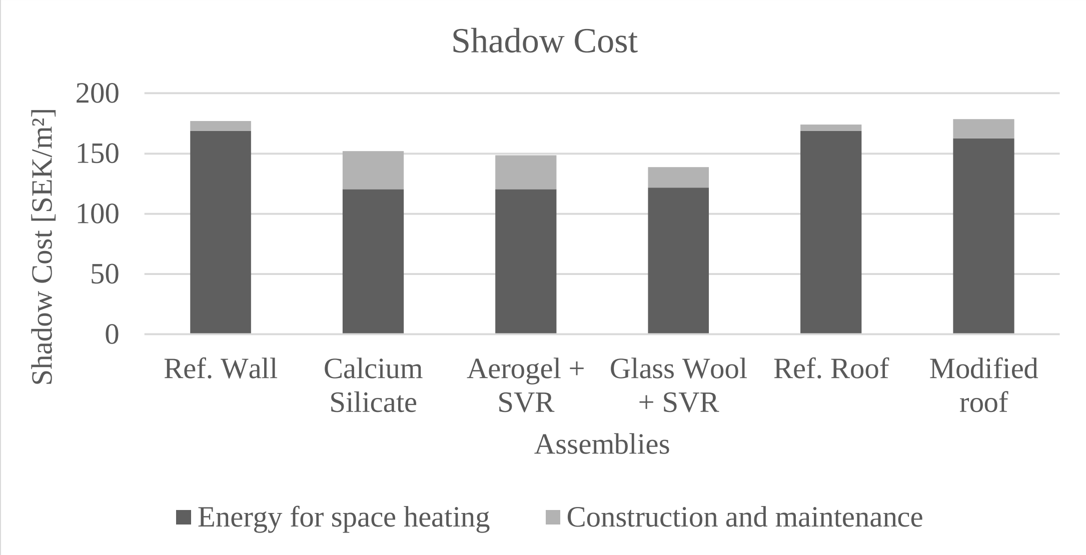


Figure 181: Shadow Cost for the V-building, calculated by unit floor area.

In addition to calculating the overall shadow cost for the assemblies, also the shadow cost for the individual environmental impact indicators were considered, which are shown in Figure 182-183. The results showed that common for all the assemblies was that the global warming potential accounted for the largest share of the total shadow cost, followed by the acidification potential. These two environmental impact indicators alone showed to be accountable for approximately 80-85% of the total shadow cost. The lowest contribution was due to the ozone depletion potential, which was shown to account for less than 0.005% of the total shadow cost.

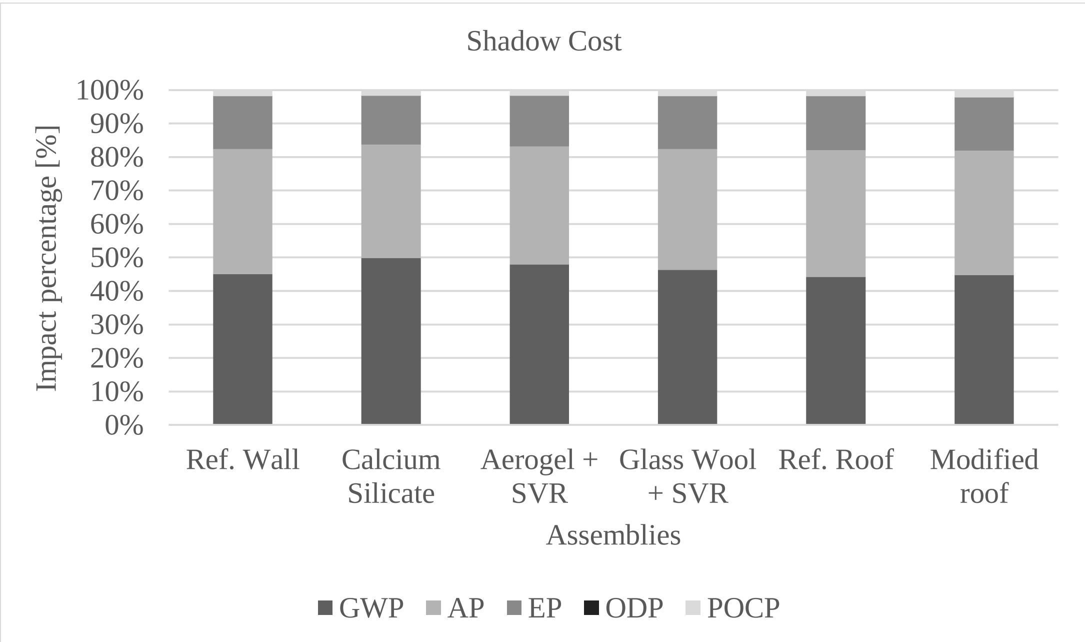


Figure 182: Shadow Cost separated by environmental impact indicator for the A-building.

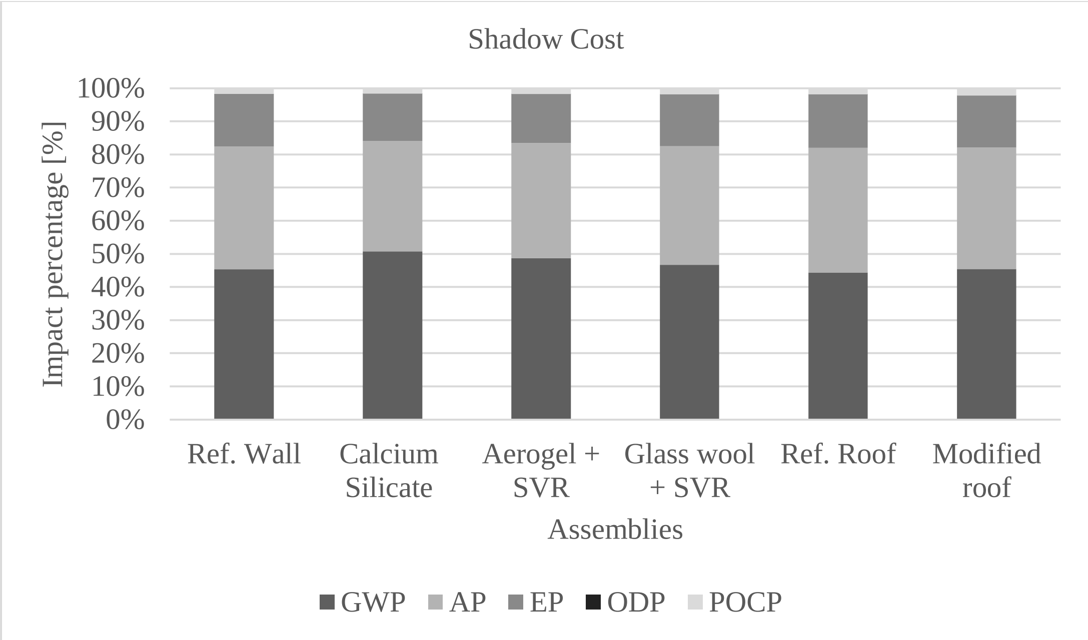


Figure 183: Shadow Cost separated by environmental impact indicator for the V-building.

7 Discussion

The following sub-chapters discusses the results obtained by the hygrothermal-, thermal bridging-, and energy simulations as well as the life cycle cost and life cycle assessment for the A- and V-building

7.1 Hygrothermal Performance

This study clearly showed the difference in the hygrothermal performance of the wall assemblies caused by the retrofit with interior insulation, as both the risk of mould growth as well as the risk of freeze thaw damage increased after the retrofit. As mentioned earlier in this report the hygrothermal simulation were carried out for both North and South orientation, as it was recommended to investigate the prevailing direction of wind-driven rain as well as the North orientation. North was analysed as this orientation received least amount of sunlight. For the uncoated wall assemblies, the South orientation showed considerably larger risk for both mould growth and freeze thaw damage in comparison to the North orientation. This was due to a significantly higher amount of wind-driven rain on the South orientation, which in combination with the reduced drying of the wall caused by the interior insulation would results in a larger moisture accumulation in the wall. In contrast to the South orientation, the North orientation showed only a high risk for mould growth. Carrying out the retrofit with interior insulation showed very little difference in the temperature at monitor position one in comparison to the reference case (assembly A), while the temperature at monitor position two showed a considerably larger decrease. Common for both monitor position one and two were that all the assemblies showed a quite similar decrease in the temperature, which were related to the thermal conductance of the assemblies, as they all had a U-value of 0.37 W/(m·K).

The application of the water repellent coating on the exterior surface of the exterior wall showed to effectively eliminate the risk of freeze thaw damage, as the water repellent coating blocks the wind-driven rain from being absorbed by the existing brick wall. In addition of eliminate the risk of freeze thaw damage, the water repellent coating also caused a major reduction in the risk of mould growth. Which brought the four CaSi assemblies, the two smart vapour retarder assemblies as well as the Sto-Therm assembly (assemblies F, G, H, I, N, O, and R) below 10% of the time where the preconditions for mould growth were met. Of which the two smart vapour retarder assemblies showed the best performance. Despite the fact that some of the assemblies showed a higher percentage of time where the preconditions for mould growth were met, it may not necessarily mean that assembly will experience mould problems. As some of the assemblies consist exclusively of materials which are unreceptive to mould growth, however, these assemblies were still sorted away. As there still is the risk of organic residues being present at the interface between the existing wall construction and the new interior insulation assembly, which was where the high risk of mould growth was noticed for the assemblies sorted away. The results from this study regarding the application of the water repellent coating in combination with interior retrofit corroborate with the conclusions drawn by Bjarløv et al. (2015) after their case study, through numerical simulations investigating interior use of capillary active insulation with water repellent coating on the exterior surface.

The reference periods as well as the future climate scenarios showed only a small increase in the water content in the wall assemblies with the water repellent coating, however this increase were not high enough to cause any risk for freeze thaw damage. It was assumed that the water repellent coating would still block the wind-driven rain from striking the wall surface and being absorbed, and that the increase in the water content may be related more to moisture from the interior side, as the increase in the water content was relatively small. With respect to the risk of mould growth, most of the wall assemblies showed better performance with reference periods as well as the future climate scenarios when compared to the current climate data, as the percentage of time where the preconditions for mould growth were met was reduced. Despite this reduction, a small increase was noticed between the different time periods. It was assumed that the reduction was caused by the fact that the current climate simulations was carried out using a Typical Meteorological Year (TMY) climate data set which was then repeated 30 times during the 30-year simulations. This could potentially show considerably different results from the simulations using the reference periods or the future climate scenarios, where each year during the 30-year period would different from the others. The only exception for this reduction was the Sto-Therm assembly, which showed worse results for the two reference periods as well as the CNRM climate scenarios for the time period 2071-2100. As seen for the current climate data, the smart vapour retarder assemblies showed the best performance over the capillary active assemblies. These results corroborate the conclusions drawn by Vereecken (2014) and (2015) where she studied the hygrothermal performance of capillary active assemblies (CaSi, AAC, and wood fibre) in comparison to traditional retrofit assemblies using a smart vapour retarder. From where she concluded that the traditional retrofit assemblies with the smart vapour retarder would outperform the capillary active assemblies with respect to both moisture and energy performance. Regarding the temperature in the wall assemblies, very little difference was noticed for monitor one when comparing the reference period and the future climate scenarios to the current climate data. In contrast to monitor one, the temperature at monitor two showed a small increase between the time periods.

As for the roof assemblies, the study showed promising results for several of the modified construction. Especially the smart vapour retarder assembly as well as the ventilated roof assemblies with the exterior OSB and EPS (assemblies D, E, and G) showed good results, as these assemblies maintained relative humidity levels below the critical level of 75% for the vast majority of the 30-year time period. The importance of the smart vapour retarder was shown when compared with the almost identical roof assembly F which was using a traditional PE-foil as vapour retarder. By applying the smart vapour retarder, the percentage of time above the critical level was reduced from more than 60% to less than 5% at monitor one, while causing a reduction from more than 30% to less than 10% at monitor two. Which corroborate the conclusions drawn by Künzel (1999) that smart vapour retarders would effectively reduce the risk of moisture problems in the building envelope, due to the increased rate of drying out. Although the ventilated roof assemblies already do maintain relative humidity levels below the critical level of 75% for the vast majority of the time period, it is possible that the application of a smart vapour retarder would improve the hygrothermal performance even more, making the ventilated roof assemblies even more suitable for the future climate conditions. In addition to the promising results assemblies D, E and G, the study also showed how the initial conditions can have a large effect on the results for some of the roof assemblies. As the exterior insulated concrete roof (assembly H) with the default initial relative humidity of 80% showed a very high risk of mould growth occurring, but with a steady decline in the relative humidity. The decline in the relative humidity would continue until the construction met its equilibrium, which happened to be below 70% relative humidity.

It was due to the slow decline in the relative humidity, that assembly H failed, since it would take the assembly 5-8 years to reach relative humidity levels below the critical level of 75%. As mentioned earlier in this report, simply lowering the initial relative humidity from 80% to 70%, which was considered as relatively easy to achieve, would results in a construction maintaining relative humidity levels below the critical level of 75% for the entire 30-year time period.

For the roof assemblies at monitor one, the reference periods as well as the future climate scenarios showed almost no difference for the two unventilated assemblies (assemblies G and H70), while the two ventilated assemblies (assemblies D and E) experienced a slight increase in the relative humidity between the time periods. Which could be related to the changing relative humidity and temperature conditions in the ventilated air cavity in the ventilated roof assemblies. Also at monitor two, the two unventilated assemblies showed better performance that the unventilated assemblies. Common for both monitor positions were that the CNRM climate scenarios showed slightly worse results when compared to the IPSL climate scenarios. These differences are related to differences between the two global climate models used for the climate scenarios, which could in turn be related to different initial conditions of the global climate models. Regarding the changes in the temperatures, at monitor one it was shown that the upper 25% of the temperature values would not experience much change, while the lower 25% of the temperature values showed a decrease, meaning that more extreme cold temperature will occur in the future. Also at monitor two, the temperatures show very little change for the upper 25%, while the lower 25% showed a decrease.

7.2 Thermal Bridging

As mentioned earlier in this report, only the exterior insulation concrete roof assembly (assembly H70) was simulated in HEAT2, although three roof assemblies (D, G, and H70) were taken further to the energy simulation. Which was due to the fact that the energy simulation software would only accept one Ψ-value for each junction type, and as the exterior insulation concrete roof assembly covered the majority of the roof areas, this assembly was chosen for HEAT2. In case of a more detailed study of the thermal bridges, it would be possible to calculate the percentage of the total roof eave junction area for each of the three roof assemblies, and then calculate an average Ψ-value which could be used for the entire building. Assigning an average Ψ-value for the entire building could possibly ensure more accurate simulation results for the thermal bridging's. In addition to the limitation of the roof eave junction, only four junctions were carried out for this study while the remaining junctions were set as typical in the energy simulation software, which was yet another limitation for the thermal bridging simulation. Only four junctions were chosen due to simplicity reasons as well as a lack of drawing material concerning certain junctions.

7.3 Energy Performance

From the energy simulations it was shown that a retrofit of the exterior walls could result in a reduction of the energy demand for space heating by approximately 20-25% for the A-building, while a 25-30% reduction was shown for the V-building. A retrofit of the roof construction showed the potential to reduce the energy demand for space heating by approximately 5% for both buildings. The large difference for the cooling demand was the result of carrying out the energy simulations the two buildings in three different simulation software. Design Builder and Honeybee which both used the EnergyPlus simulation engine showed a difference by approximately 30%. IDA ICE however, used a different simulation engine, which showed mainly a large difference when compared to the Honeybee results by approximately 100%, while only 40% to Design Builder. Although the percentage difference seems quite large, the actual difference between the simulation software was actually relatively small, approximately 0.4-0.8 kWh/m^2. It was assumed that the differences between the simulation results were related to the differences in the simulation engines as well as the difference in the inputs possibilities. The difference in inputs possibilities is relevant as the simulation software have different amount and types of input options. If some input options were not available in the other software, these inputs were left either as default or set to typical, depending on the input type. And as the cooling demand of the buildings was quite small to begin with, then it was assumed that the any small differences in the input data could be the reason for these differences between the three software.

From the energy simulations with the future climate scenarios carried out in IDA ICE it was shown that 3-8% reduction of the energy demand for space heating would occur for the reference case for both buildings between the three time periods. The reference cases for the two buildings showed a similar curve for the heating demand. Which showed a more or less continuous growth during the year. Also the modified wall and roof cases showed a similar curve for the heating demand during the course of the year. Regarding the cooling demand from the energy simulations with the future climate scenarios, it was shown that the cooling demand would experience an increase between the different time periods. For most of the future climate scenarios and increase between 15-70% was noticed, which was common for both buildings. The only exception was the CNRM RCP45 climate scenario between the two last time periods, which showed only a slight increase 1-2%.

It was assumed that any minor differences between the two buildings with regards to the percentage increases or decreases of the heating/cooling demand was related to the difference in the geometry, window to wall ratio as well as the interior heat gains. As the simulation cases for the two buildings were derived from on the same base template, which included all the necessary settings. Everything from properties of the building envelope to the schedules and ventilation settings. The template was designed so that the only differences between the two buildings would be related to the building geometry, window to wall ratio and interior heating gains, which was set according to the given drawing material and specification concerning zone activities.

7.4 Life Cycle Cost

From this study it was shown that although a 20-30% reduction of the heating demand for the wall cases and a 5% reduction for the roof cases was achieved, there would be no economic background carrying out the retrofitting work of neither the wall- or roof constructions. It was assumed that it would quite hard to achieve an energy reduction large enough to make the investment profitable for the owner by retrofitting the A- and V-building through interior retrofitting. The retrofitting work should only be carried out if the wall- or roof constructions would be in need of renovation regardless of the wish of carrying of the energy retrofit. Combining the necessary renovation of the buildings with the energy retrofit would carry the potential to cut away a large portion of the costs related to the running the building site (e.g. for rent of machinery and equipment) as well as for the construction work itself. In addition to combining the necessary renovation with the energy retrofit, an additional portion of the costs could potentially be cut away by combining the energy retrofitting of the roof- and wall constructions. As a number of the activities are making use of the same site equipment and machinery. Additionally, a window replacement could be incorporated into the energy retrofit as well, this would increase the energy saving potential while simultaneously reducing the construction- and site costs for each of the retrofitting measures.

A comparison between the two buildings showed higher costs for the retrofitting measures in the A-building than in the V-building. Which was shown to be due to a smaller reduction of the heating demand by the retrofitting measures in the A-building, which would in turn make the retrofitting measures less profitable for the A-building. One reason for the large economic infeasibility of the modified roof constructions, could be due to the small percentage of the existing roof which had poor roof construction. This would lower the overall economic feasibility of the modified roof constructions. Looking specifically at the wall cases, although causing almost the same reduction of the heating demand, the two assemblies using the innovative insulation materials showed to be considerably more expensive than the traditional assembly using the smart vapour retarder. As the material price of the insulation was significantly higher for the CaSi and aerogel insulation than the glass wool. Not even the reduced space loss costs due the aerogel insulation would show profitable compared with the traditional wall assembly with glass wool and the smart vapour retarder.

Regarding the cooling demand which was determined by the energy simulation, these was not included in the LCC. As the given data specified that the buildings had its own “free” cooling system, and no specific details were provided about the type cooling system or any cost related to it. Depending on how the cooling system actually works and its cooling capacity, neglecting the cooling demand from the LCC would definitely affect the results of the calculations, possibly even change the order of which assemblies proved to be most profitable. In addition to the limitation regarding the cooling demand, it should also be emphasized that the results from the LCC calculation are very sensitive to the interest and growth rates, which were mentioned in section 5.8. As a result of unrealistic alterations (high as well as low) of the interest and growth rates, any assembly can be made profitable or non- profitable. It should also be noted that the data used for material costs and machinery rent were based upon industry average or by pricing lists from specific companies, some costs may therefore differ a lot depending on the actual supplier or trade contractor.

7.5 Life Cycle Assessment

In contrast to the LCC, the modified wall cases were shown to be environmental feasible from the LCA perspective, and based on the overall assessment wall assembly O (glass wool with smart vapour retarder) was shown to cause the lowest environmental impact. In addition to the overall assessment, wall assembly O was also shown to perform the best in a number of the individual environmental impact indications. In the same way as with the LCC, the modified cases were shown to perform better in the V-building than in the A-building. Which was generally due to the smaller reduction of the heating demand in the A-building caused by the modified wall and roof cases, in comparison to the V-building, as described in section 7.4.

As mentioned earlier in this report, most of the environmental impact indicators showed a large reduction as a result of the modified wall cases, with the exception of the ODP for the aerogel wall cases (assembly N). In addition, the POCP for the modified roof cases showed a large increase. It was shown that the significantly large ODP emission for the aerogel wall cases was related to the production of the aerogel insulation itself, which showed to be three to four times higher than the other insulation materials. Regarding the POCP for the modified roof cases, the results suggested that the large POCP emission was related to the large quantities of EPS insulation used in the roof constructions.

Shadow Cost calculations showed like the environmental impact indicators, that the retrofit would be environmental beneficial for all the modified cases, with the exception of the roof cases, which showed a slight increase in comparison to the reference roof cases. In addition to the monetarization of the environmental impact indicators, the Shadow Cost method was also used to determine the overall impact by the individual environmental impact indicators, as mentioned earlier in this report. Which showed that the global warming potential and the acidification potential accounted for the largest shares, with 80-85% of the total shadow cost. One limitation related to the Shadow Cost method and the possibility of comparing projects, is the difference in value judgments for each of the environmental impact indicators depending on the geographical location. The difference in the value judgments is often depending on what environmental impact indicators are seen as being the worst for that specific location, and as a result of different value judgments a comparison between projects can be hard.

Another limitation for the LCA in this study was related to the life-cycle stages and the environmental impact indicators. As the LCA did not include all of life-cycle stages nor all the possible impact indicators, which was due to limited information in the EPDs for the material used in suggested construction. To ensure correct results and a valid comparison between the reference cases and the modified cases, it was important that all the materials included in the LCA used the same life-cycle stages as well as impact indicators. As mentioned earlier, the only stages included in the LCA were supply of raw materials, transport and manufacturing, while the included impact indicators were GWP100, AP, EP, ODP, and POCP. However, if the LCA had included all the life-cycle stages from supply of raw materials to the recycle potential as well as all the environmental impact indicators related to each of the stages, the LCA would then show a significantly more accurate result of the environmental impact caused by the different cases. This problem of limited information in the EPDs is possibly related to “loose” demands stated by the ISO Standard 14025, regarding the extent of the information provided to be assigned a product EPD.

8 Conclusion

The main conclusions which were drawn from this study are summarized as follows:

- The application of a water repellent coating is vital for the long term hygrothermal performance of a retrofit with interior insulation where the exterior surface is exposed to wind-driven rain. As the interior insulation reduces the drying out rate of the existing wall construction, which means that without the water repellent coating moisture will accumulate and increase the risk of both mould growth and freeze thaw damage.
- Applying a smart vapour retarder to a traditional glass wool insulated stud wall assembly with interior plasterboard will outperform the capillary active assemblies as well as the traditional assemblies using a regular vapour retarder with respect to hygrothermal performance. Although this is only true if a water repellent coating is used for exterior surface. If no water repellent coating is applied, then the Calcium Silicate, Autoclaved Aerated Concrete, Sto-Therm, as well as insulating Perlite plaster assemblies will outperform all the vapour tight assemblies including the smart vapour retarder assembly. This is due to the high amount of moisture introduced from the exterior side, which the capillary active assemblies to some extent will redistribute and realise to the indoor air resulting in an overall lower water content in the wall. However, without the water repellent coating no assembly would be free from the risk of mould growth or freeze thaw damages.
- Placing an oriented strand board (OSB) as well as EPS insulation on the exterior side of the ventilated air cavity in a ventilated roof construction, will greatly reduce the risk of mould growth in the construction. As the exterior insulation will reduce the heat losses due to long wave radiation.
- Applying a smart vapour retarder to an unventilated roof construction with a wooden beam structure and bitumen felt as external cladding material, will result in a greatly reduce risk of mould growth in the construction, compared with a similar construction using a regular vapour retarder. As the smart vapour retarder allow the roof construction to dry out during the warm summer months.
- The effectiveness of the retrofitting measures is expected to result in a reduction of the energy demand for space heating by 20-30% for the retrofitted wall assemblies, and a reduction of 5% for the retrofitted roof constructions. As for the cooling demand, both buildings are expected to not show much change in the cooling demand due to the retrofitted measures.
- A water repellent coating for the retrofitted wall assemblies as well as smart vapour retarder for the roof construction will ensure good hygrothermal performance with respect to the impact of climate change. Common for most cases (retrofitted and reference cases) is that the annual energy demand for space heating is expected to experience a slight decrease in the future due to the impact of climate change, simultaneously with relative large increase in the annual energy demand for space cooling.
- From an economic perspective, retrofitting the exterior wall- or roof constructions of an existing building to reduce the operational costs is likely to be economic infeasible. As the energy savings will not offset the construction costs for carrying out the retrofit. Such a retrofit should only be carried out if the exterior wall- or roof

constructions is in need of renovation regardless of the wish of carrying out the energy retrofit. The retrofitting measures were shown have a life cycle cost 32-66% higher than the reference cases, corresponding to a cost difference of approximately 10-18 million SEK for the A-building and 15-27 million SEK for the V-building over the 50-year period.

- From an environmental perspective, retrofitting the exterior wall constructions of an existing buildings has the potential to be environmental feasible, since the thermal performance of the existing wall constructions had a really poor of 1.2 W/(m^2·K). As the exterior wall retrofitting measures were shown to have an environmental impact approximately 10-22% lower than the reference cases, based on the Shadow Cost calculations. In contrast to the exterior wall construction, the roof constructions did not have the potential to be environmental feasible. The environmental impact of the roof retrofitting measures was shown to be approximately 0.5-2.5% higher than the reference cases.
- The building geometry, window to wall ratio as well as interior heat gains will affect the energy saving potential of applying the retrofitting measures to multiple buildings with similar climate conditions and building envelope. As these factor greatly determines the losses and gains of the building.

Author’s recommendations:

- In case of an energy retrofit using interior insulation, to combine a traditional setup (cheap glass wool insulation and studs) with a smart vapour retarder, wet room plasterboard and a water repellent coating on the exterior surfaces would prove more economic- and environmental feasible over using the innovative insulation products such as Calcium Silicate and Aerogel insulation. As the prices of the innovative insulation products are considerably higher than regular glass wool.
- The water repellent coating on the exterior surfaces is of great importance in ensuring a good hygrothermal performance of the exterior wall. The water repellent coating by itself will do a great deal for the performance of the exterior wall, as it will block rain penetration. Blocking rain penetration will lower the risk of moisture related problems as well as dry out the existing brick wall, which will result better thermal performance of the brick.
- It would not be advised to retrofit the major part of existing roof constructions, as it were retrofitted as recent as 2011 and was deemed to be in good condition. However, certain roof areas (level six copper- and bitumen felt roof) might benefit from an energy retrofit, as they are quite inefficient (U-value of 0.7 and 0.27 W/(m^2·K) respectively) and likely to be subject to moisture related problems.
- If a roof retrofit is to be carried out, it would then be suggested to use a ventilated roof setup with exterior EPS insulation and OSB or an unventilated setup with a smart vapour retarder for the incline roof areas. While a traditional exterior insulated concrete deck using EPS insulation and bitumen felt would be suggested for the flat roof areas, however, the construction process should ensure some sort of rain protection to keep the relative humidity of the roof below the critical limit.

9 Further Research

This work clearly showed no economic feasibility in carrying out an energy retrofit with the wall- or roof measured assessed in this study. Further research could however be carried out as mentioned in the discussion, to bundle up retrofitting measures such as wall and roof or wall, roof and window replacement, then the individual retrofitting measures might become more economic feasibility as a number of expensed could be lowered. To bundle up the retrofitting measures would most likely also increase the environmental feasibility of the energy retrofit. An addition area for further research would be to carry out similar energy simulations, LCC and LCA for the remaining buildings in the campus of Lund University by Klas Anshelm, to establish a better correlation between the suggested retrofitting measures and the possible energy savings.

10 Summary

In recent years' climate change has become generally accepted as a potential problem, and the increased awareness regarding the possible future consequences have resulted in an increased amount of incentive towards sustainability worldwide. The increased incentive has affected the building industry in the form of several new demands regarding energy efficiency and preparation work towards probable future climate conditions. Preparation work which includes retrofitting of the older, inefficient part of the building stock. Due to the often poor energy performance, the older part of the building stock yield great potential towards energy savings. However, despite the energy saving potential and good reasoning, retrofitting older buildings may lead to severe moisture problems, as a result of a change in the hygrothermal behaviour of the constructions. In addition to this, the predicted increase in precipitation and extreme weather events in the future poses an increased risk for the moisture performance of buildings. Lastly, a number of these older building might be placed under a cultural protection by the authorities. These cultural protections may prevent the use of the more efficient and secure methods of retrofitting, if these is a risk that these methods could compromise the aesthetical values of the buildings. This will in turn make the retrofitting of the building riskier with regards to the moisture performance.

The objective of this study was to assess the long term performance of various energy retrofitting measures for the exterior wall and roof constructions with respect to energy- and moisture performance. Where the major focus was placed on retrofitting the exterior wall with interior insulation solutions, while a smaller focus was placed on retrofitting the roof construction. The economic- and environmental feasibility of the retrofitting measures were also taken into consideration through Life Cycle Cost (LCC) and Life Cycle Assessment (LCA). The assessment was carried out for two cultural protected school buildings in the campus of Lund University, which were the School of Architecture (A-building), and the building for civil engineering (V-building). Both buildings were a part of the Faculty of Engineering at Lund University in southern Sweden.

The study was carried out in six phases. *A literature review phase*, where the existing constructions were assessed and relevant literature was reviewed. The literature review phase would determine the extent of the existing knowledge as well as serve to generate ideas for construction solutions. *A project goals phase*, where project goals, simulation cases and expected results were defined. *A moisture assessment phase*, where wall- and roof assemblies were developed based upon the literature review, and the hygrothermal performance was simulated in the software WUFI Pro against current climate data as well as future climate scenarios. In the moisture study of the future climate scenarios, two 30-year time periods were used, which were 2021-2050 and 2071-2100. In addition to this, a reference period was used, which was 1961-1990. All three time periods were simulated using two different Global Climate Models (GCMs). The indicators used for the assessment of the moisture performance were the risk of freeze thaw damage and mould growth. *A thermal bridging phase*, where the thermal bridging effect of the approved assemblies (from the moisture assessment phase) were simulated in the software HEAT2. *An energy performance phase*, where the approved assemblies and results from thermal bridging simulation in HEAT2 were implemented into the whole-building energy simulations (carried out in the software Design Builder, Honeybee, and IDA ICE). The whole-building energy simulations with current climate data were carried out using all three software, while for the future climate scenarios only the software IDA ICE was used. In the energy study of the future climate scenarios, three TDY (typical downscaled year) data sets were used, which represented the three time periods 2009-2038, 2039-2068, and 2069-2098. For each TDY data sets three different Global Climate Models (GCMs) were used. The indicators used for the assessment of the energy performance were the heating- and cooling demand. Lastly, *a feasibility phase*, where the feasibility of the approved assemblies was studied with respect to LCC and LCA, taking into account the material usage for each of the assemblies and energy use from the energy simulations. Both the Life Cycle Cost as well as the Life Cycle Assessment were calculated over a 50-year period. Under the LCA, five environmental impact indicators were assessed, which were: Global Warming Potential for 100 years, Ozone Depletion Potential, Photochemical Oxidation Creation Potential, Acidification Potential, and Eutrophication Potential. The environmental impact indicators were assessed individually as well as combined using the Dutch "Shadow Cost" method. The Shadow Cost method assigns a monetary value on each of the environmental impact indicators, thus making it possible to add together the impact from each of the indicators.

From the study it was concluded that the application of a water repellent coating is vital for the long term hygrothermal performance when retrofitting with interior insulation. As the interior insulation will reduce the drying out rate of the existing wall construction resulting in a moisture accumulation within the wall. None of the wall assemblies passed both the mould growth- and freeze thaw criteria without the water repellent coating. Looking at the individual wall assemblies, it was shown that the smart vapour retarder assemblies would outperform both the capillary active assemblies, the traditional PE-foil assemblies as well as the innovative PE-foil assemblies (such as VIP or Aerogel insulation), with respect to the hygrothermal performance. In addition to the wall assemblies, the smart vapour retarder was also shown to be beneficial for the unventilated roof assemblies, replacing the traditional PE-foil. As for the ventilated roof assemblies, placing an oriented strand board (OSB) as well as EPS insulation on the exterior side of the ventilated air cavity was shown to great lower the risk of mould growth as these measures would reduce the heat losses due to long wave radiation.

Regarding the energy performance of the retrofitting measures, with the current climate data a reduction of the energy demand for space heating by 20-30% for the retrofitted wall assemblies, and 5% for the retrofitted roof constructions is expected. The already low cooling demand on the other hand, did not show much change from the retrofitting measures. For the future climate scenarios, the annual energy demand for space heating is expected to experience a slight decrease of 5-8%, while the annual energy demand for space cooling is expected to experience a relative large increase of 15-70% between the different time periods.

Lastly, it was concluded that there is no economic feasibility in carrying out a retrofit of the existing exterior wall- or roof constructions. As the energy savings will not offset the construction costs for carrying out the retrofit. The retrofitting measures were shown have a life cycle cost 32-66% higher than the reference cases. For the environmental feasibility, only retrofitting the exterior walls had the potential to be environmental feasibility. As the existing wall constructions had a really poor thermal performance of 1.2 $W/(m^2 \cdot K)$, yielding great potential for improvement. The wall measures were shown to be 10-22% lower than the reference cases, while the roof measures were approximately 0.5-2.5% higher.

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12 Appendix

12.1 Appendix A

Table 30: Specifications for WUFI materials

Material	Bulk Density [kg/m^3]	Porosity [m^3/m^3]	Specific Heat [J/(kg·K)]	Thermal Conductivity [W/(m·K)]	Water Vapour Diffusion Resistance Factor
Building paper 60 minutes	280	0.001	1500	12.000	144
Agepan OSB	616	0.52	2100	0.130	144
Agepan THD	226	0.79	2100	0.047	3.4
Air Layer	1.3	0.999	1000	0.280	0.32
Aspen Aerogel Spaceloft	146	0.92	1000	0.014	4.7
Calcium silicate AI	222	0.92	1303	0.057	5.4
Calcium silicate Masea	270	0.90	1162	0.062	3.8
Calcium silicate Lüneburg	230	0.90	920	0.050	3.23
Calcium silicate Washington	230	0.90	920	0.050	2.93
Cement board	1130	0.48	840	0.255	28
Cement lime plaster	1900	0.24	850	0.800	19
Concrete C12/15	2200	0.18	850	1.600	92
EPS	30	0.95	1500	0.040	50
Gypsum plaster /plasterboard	850	0.65	850	0.280	8.3
Homatherm ID-Q11	135	0.90	2100	0.038	2.1
Interior perlite plaster	338	0.87	850	0.030	6.2
Isover glass wool ZKF 032	33	0.95	840	0.032	1
Mineral wool	60	0.95	850	0.040	1.3
PA-membrane SVR	65	0.001	2300	2.900	4380
Plywood board	500	0.50	1500	0.100	700
Remmers IQ-Fix adhesive	1313	0.50	863	0.497	18.7
Remmers IQ-Therm	45	0.98	1400	0.031	69
Remmers IQ-Top plaster	466	0.81	1173	0.106	8.4
Solid brick masonry	1900	0.24	850	0.600	10
Stolevell in mineral	1330	0.50	850	0.870	23
Sto perlite insulation board	100	0.96	850	0.042	8
Vapour retarder S_d=100m	130	0.001	2300	2.300	100000
VIP Generic	200	0.001	800	0.007	1500000
VIP Isover Vacupad	171	0.95	1050	0.009	1000000
Ytong multiport adhesive	833	0.686	850	0.155	15.1
Ytong multiport blocks	115	0.96	850	0.040	4.1
Ytong south aerated concrete	386	0.85	850	0.072	9.9

12.2 Appendix B

Table 31: External Wall Assemblies in WUFI

Model ID	Material layers (Exterior to interior)	Layer Thickness [m]	Total Thickness [m]	U-value [W/(m²·K)]
A (Base Case)	Solid Masonry brick Gypsum plaster	0.395 0.015	0.410	1.20
B	Mineral wool Vapour retarder S_d=100m Gypsum plasterboard	0.075 0.001 0.013	0.089	0.37**
C	EPS Vapour retarder S_d=100m Gypsum plasterboard	0.075 0.001 0.013	0.089	0.37**
D	VIP Generic EPS Vapour retarder S_d=100m Gypsum plasterboard	0.008 0.030 0.001 0.013	0.052	0.37**
E	VIP Isover Vacupad EPS Vapour retarder S_d=100m Gypsum plasterboard	0.010 0.030 0.001 0.013	0.054	0.37**
F*	Cement lime plaster Remmers IQ-Fix adhesive Calcium silicate AI Remmers IQ-Top plaster	0.015 0.007 0.110 0.010	0.142	0.37**
G*	Cement lime plaster Remmers IQ-Fix adhesive Calcium silicate Lüneburg Remmers IQ-Top plaster	0.015 0.007 0.095 0.010	0.127	0.37**
H*	Cement lime plaster Remmers IQ-Fix adhesive Calcium silicate Washington Remmers IQ-Top plaster	0.015 0.007 0.097 0.010	0.129	0.37**
I*	Cement lime plaster Remmers IQ-Fix adhesive Calcium silicate Masea Remmers IQ-Top plaster	0.015 0.007 0.128 0.010	0.160	0.37**
J*	Cement lime plaster Remmers IQ-Fix adhesive Remmers IQ-Therm Remmers IQ-Top plaster	0.015 0.007 0.060 0.010	0.092	0.37**
K*	Ytong multipor adhesive Ytong multipor block Remmers IQ-Top plaster	0.006 0.082 0.010	0.098	0.37**
L*	Ytong multipor adhesive Ytong south aerated concrete Remmers IQ-Top plaster	0.006 0.156 0.010	0.172	0.37**
M	Cement lime plaster Aspen Aerogel Spaceloft	0.010 0.027	0.058	0.37**

	Vapour retarder sd=100m	0.001		
	Gypsum plaster	0.010		
	Gypsum plaster	0.010		
N	Cement lime plaster	0.010	0.076	0.37**
	Aspen Aerogel Spaceloft	0.027		
	PA-membrane SVR	0.001		
	Air Cavity	0.025		
	Gypsum plasterboard	0.013		
O	Isover glass wool ZKF 032	0.060	0.074	0.37**
	PA-membrane SVR	0.001		
	Gypsum plasterboard	0.013		
P*	Cement lime plaster	0.015	0.108	0.37**
	Homatherm ID-Q11	0.078		
	Gypsum plasterboard	0.015		
Q*	Cement lime plaster	0.015	0.130	0.37**
	Agepan OSB	0.012		
	Agepan THD	0.088		
	Gypsum plasterboard	0.015		
R*	Stolevell in mineral	0.005	0.105	0.37**
	Sto perlite insulation board	0.080		
	Stolevell in mineral	0.010		
	Remmers IQ-Top plaster	0.010		
S	Interior perlite plaster	0.050	0.132	0.37**
	Interior perlite plaster	0.050		
	Interior perlite plaster	0.032		

*The marked solutions have by the manufacturers been described as being capillary active.
**The U-value of the interior insulation solutions include the thermal performance of the existing 395 mm solid brick masonry wall. The existing 15 mm gypsum plaster is neglected as it is assumed to be removed before applying the interior insulation.

12.3 Appendix C

Description of the Honeybee simulation scripts in Grasshopper

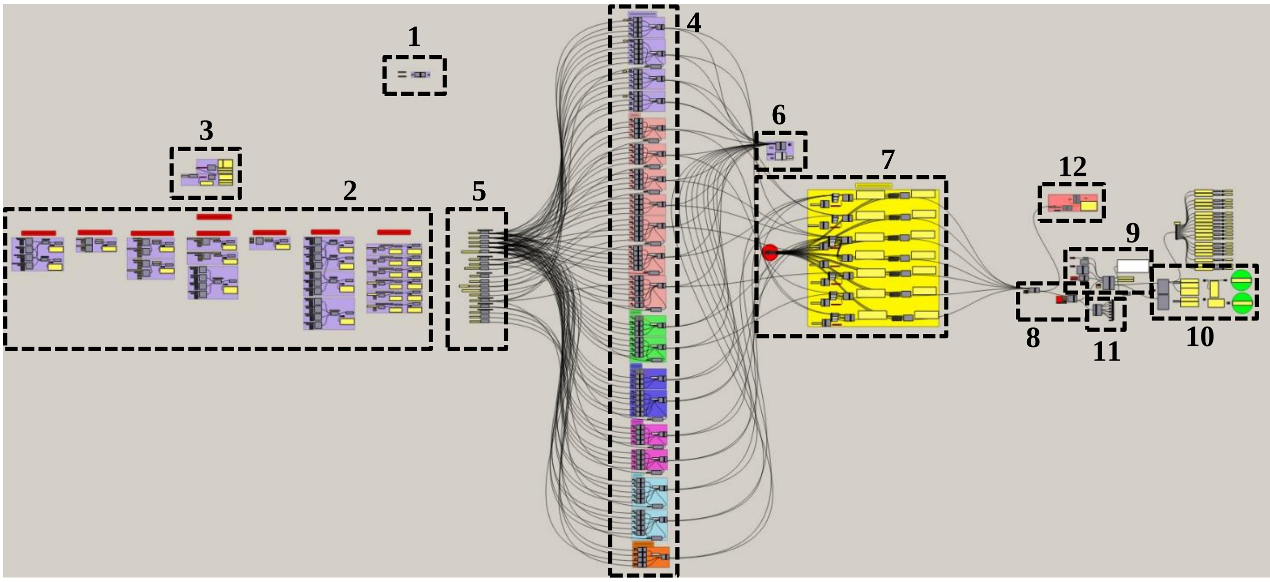

Figure 184: The full Honeybee simulation script in Grasshopper for the A-building

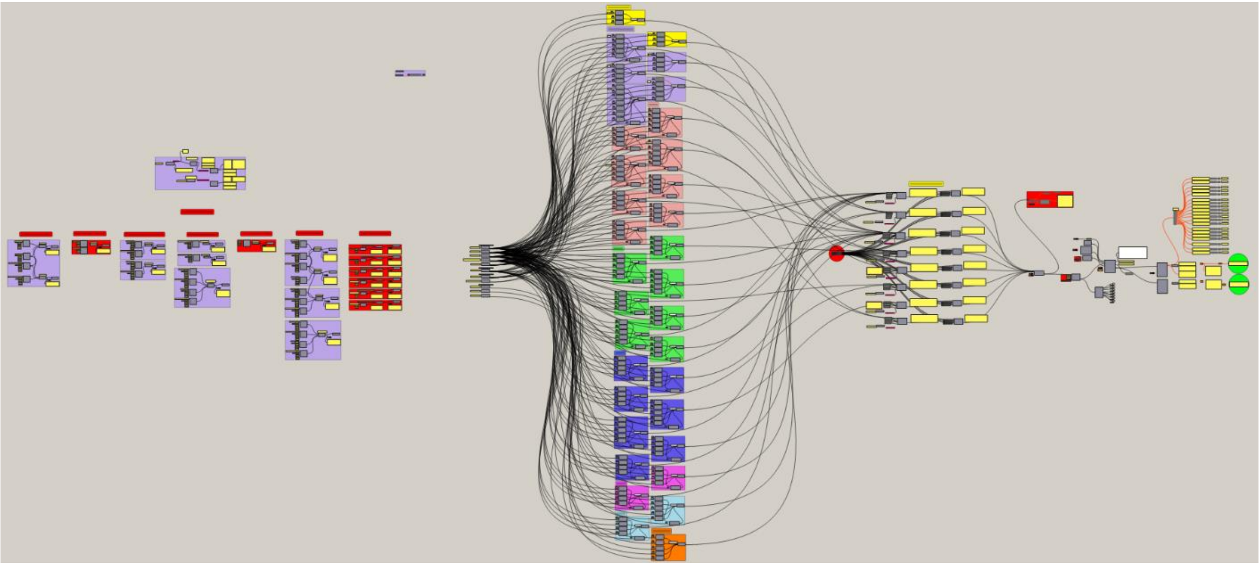

Figure 185: The full Honeybee simulation script in Grasshopper for the V-building

1. The beginning of the Honeybee script

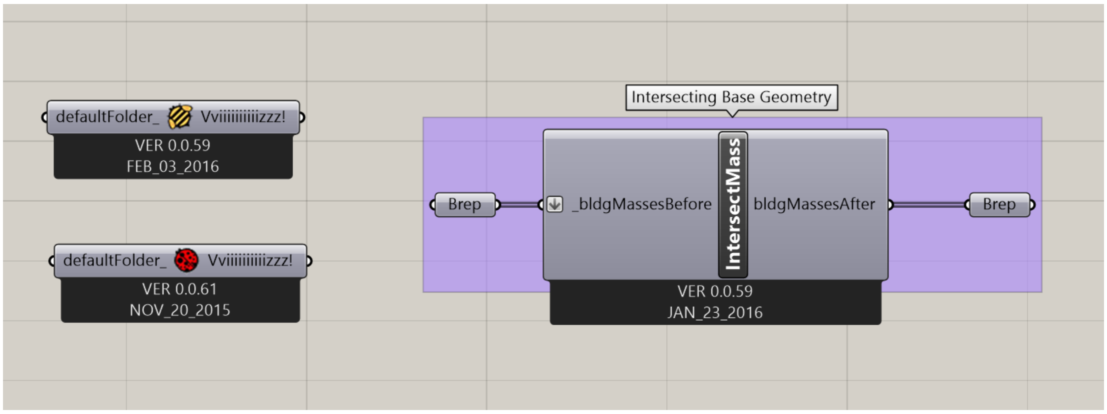

Figure 186: Getting started in Honeybee

After importing the Sketchup geometry into Rhino, the Honeybee_Honeybee- and the Ladybug_Ladybug components were dropped onto the Grasshopper canvas (the working area of the screen). The Honeybee_Honeybee- and the Ladybug_Ladybug components are the two main components in the plugins, and as a result of dropping the two components onto the canvas, Grasshopper started to load all the Python commands for both the plugins. This would in turn allow the user to use the Honeybee- and Ladybug simulation components. Another crucial task that was carried out in the very beginning of the scrip, before any zone or surface properties could be assigned, was to “intersect masses”. When model geometry is imported into Rhino, they often come in as polysurfaces, where each polysurface contains all the individual surfaces related to one zone. But when imported, the individual surfaces for each zone do not “match” with the individual surfaces of the adjacent zones. That is where the IntersectMass component comes in. By passing the model geometry through the IntersectMass component, each of the individual surfaces will then receive an “imprint” of their adjacent surfaces. These imprints will then later tell the EnergyPlus engine what surfaces matches what surfaces for the different zone geometries. The IntersectMass function are shown in Figure 186, where the original model geometry enters the IntersectMass component on the left side, and the simulation ready geometry exits the component on the right side.

2. Creating EnergyPlus constructions

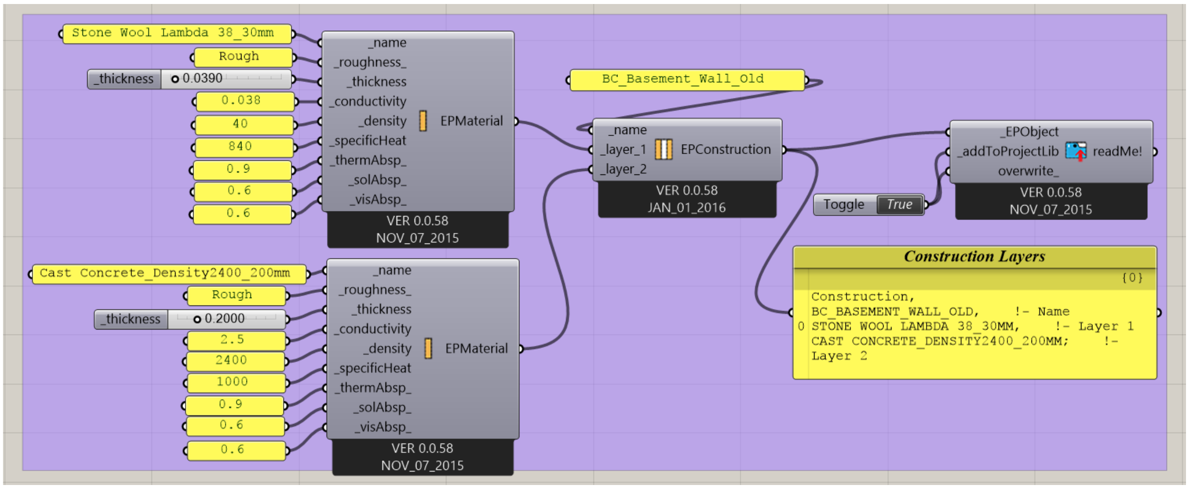

Figure 187: Creating opaque materials

Before any constructions could be assigned to the model, the constructions needed to be built up and written into the Honeybee constructions library. To build up an EnergyPlus construction in Honeybee, the EnergyPlus Opaque Material - and the EnergyPlus Constructions components were used. At the EnergyPlus Constructions component, the amount of layers was specified as well as the name of the construction (in this case the base case basement wall)[4]. When the amount of layers was specified, then the EnergyPlus Opaque Material component was used to specify the thickness and material properties for each of the layers within the construction. After completing the EnergyPlus construction, then the EnergyPlus Constructions component was connected to the Add to EnergyPlus Library component. When the toggle function was set to true on the Add to EnergyPlus Library component, then the construction had been added to the library and ready to be assigned to the model, as shown in Figure 187.

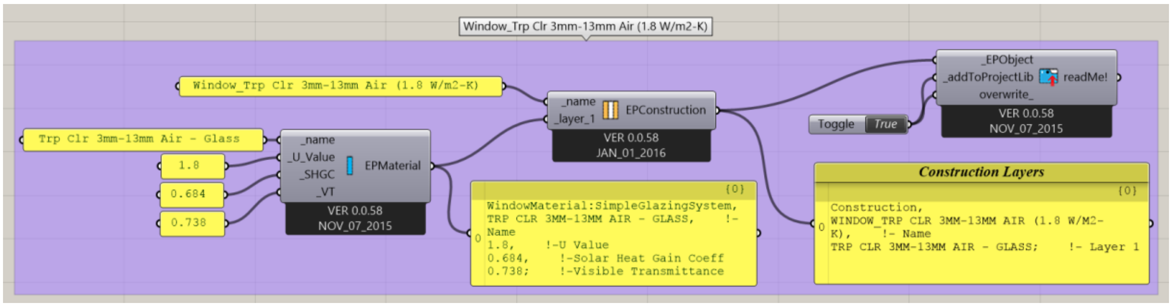

Figure 188: Creating window materials

[4] When zooming in on the EnergyPlus Constructions component, small pluses and minuses will appear. By pressing one of the pluses or minuses will add or remove a layer from the EnergyPlus Constructions component. It should be noted that layer one is always considered as the outermost layer.

An EnergyPlus window construction can be build up in a couple of ways, where one used in this study was quite similar to the method earlier for creating opaque EnergyPlus constructions. The only difference between the opaque construction and the window construction was that the EnergyPlus Opaque Material component was replaced with the EnergyPlus Window Material component. At the EnergyPlus Window Material component the window properties as well as the window name were specified. As it was seen for the opaque EnergyPlus constructions, also the EnergyPlus window construction was connected to the Add to EnergyPlus Library component, before being written into the library, as shown in Figure 188. In this study, all the constructions were built up using this method, as according to the base case constructions in Appendix K, and Table 4 for the window specifications.

3. Error checking the EnergyPlus constructions

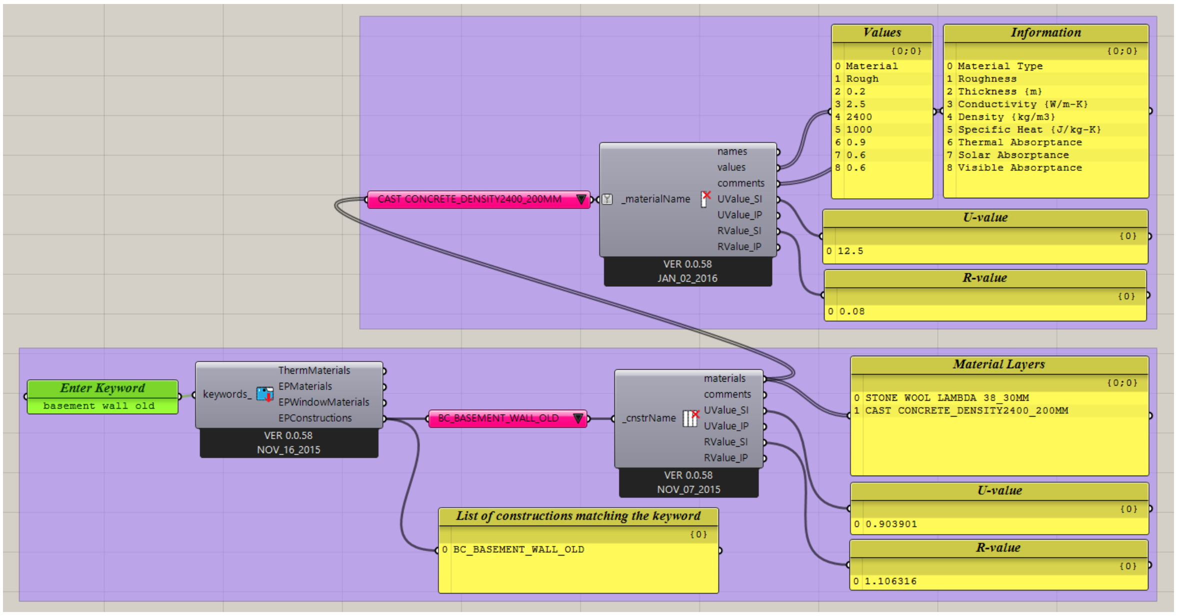

Figure 189: Error checking EnergyPlus constructions and materials

After creating the EnergyPlus constructions and materials, it was possible to check the properties of the constructions and materials to ensure that the correct values were assigned to the building later on. To check the construction and material properties, four components were needed. The four important components were the Call From EnergyPlus Construction Library, the Decompose EnergyPlus Construction, the Decompose EnergyPlus Material and the Item Selector. The Call From EnergyPlus Construction Library component allow the user to search through the EnergyPlus library to find a specific construction by entering a keyword. When the construction was found, then the Call From EnergyPlus Construction Library component was connected to the Decompose EnergyPlus Construction component. This would show all the construction information's such as the U- and R-values as well as the material layers within the construction. If it was necessary to dig further down to check the materials within the construction, then the Decompose EnergyPlus Construction component had to be connected to the Item Selector component which was then connected to the Decompose EnergyPlus Material component. As the name suggest, the Item Selector component allow the user to select between the different material layers to check the properties of each material individually. When a material layer was selected with the Item Selector and connected to the Decompose EnergyPlus Material component, then the component would show all the material properties such as density, thermal conductivity, and thickness, as shown in Figure 189.

4. Creating Honeybee surfaces and zones

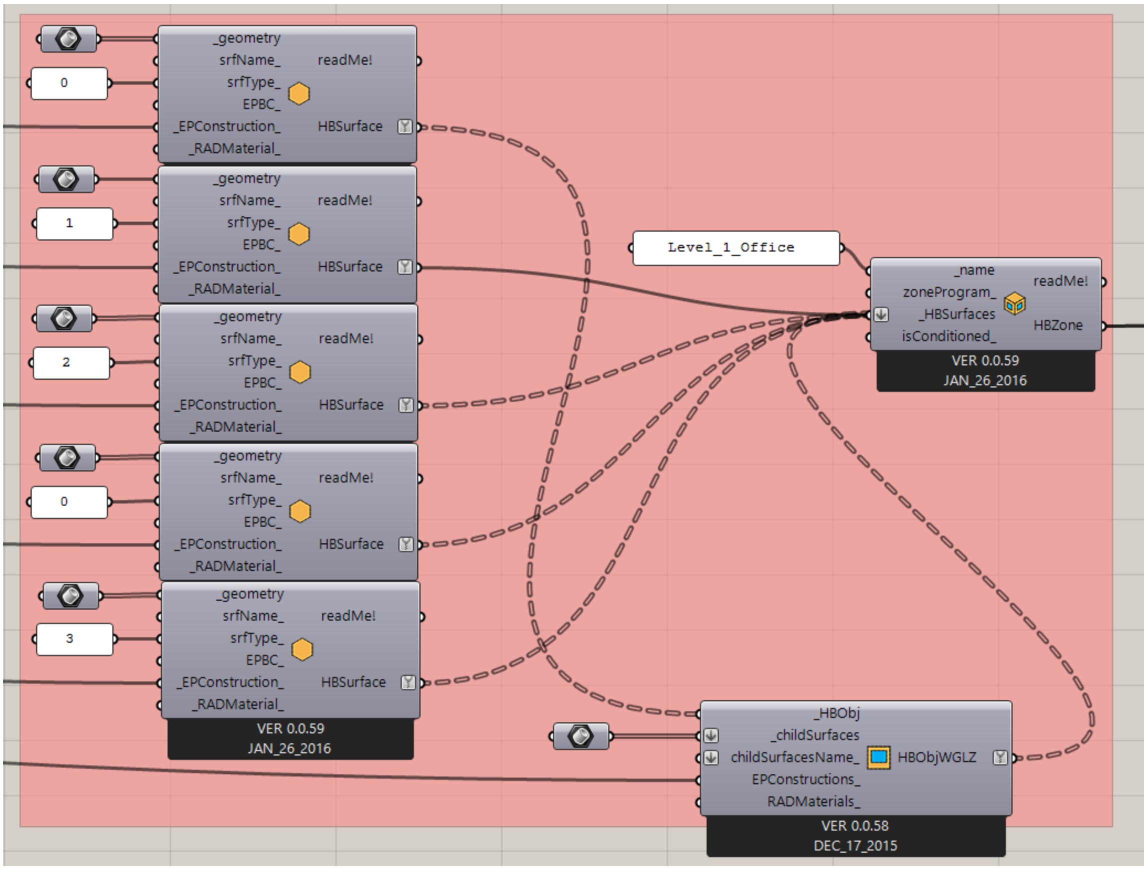

Figure 190: Creating Honeybee zones

After creating and checking the EnergyPlus construction, the Honeybee zones were created. To create a Honeybee zone, three-four components were needed, which were the Create Honeybee Zones component, the Create Honeybee Surfaces component, the Add Honeybee Glazing component, and the BREP component. The BREP component is a native Grasshopper component, not a Honeybee specific component. The BREP component links the model geometry in Rhino to the Honeybee script in Grasshopper. To create a Honeybee zone, one or more surfaces in Rhino was connected to a BREP component, and the BREP was then used as input for the "geometry" parameter in the Create Honeybee Surfaces component. Besides the geometry, the Create Honeybee Surfaces component only required one additional input to work, which was to assign an EnergyPlus construction to it. Although no other inputs were required, it was recommended to assign a surface type to the component. 12 different surface types are available in Honeybee, which are all denoted by a number. The surface types are as following: wall (0), underground wall (0.5), roof (1), underground ceiling (1.5), floor (2), underground slab (2.25), slab on grade (2.5), exposed floor (2.75), ceiling (3), air wall (4), window (5), and shading (6). If no surface types were specified by the user, then Honeybee would automatically detect the surface type for you. The automatic detection separates the surfaces based on a number of conditions hereunder inclination and location height in comparison to terrain level, which allow Honeybee to separate walls from roofs and floors, as well as to determine when a construction is considered as an "underground" construction.

If the Honeybee zone included windows or skylights, then the Add Honeybee Glazing component was used. The Add Honeybee Glazing component required the wall or roof geometry in which the windows/skylights were located, as input for the “Honeybee Object” parameter, as well as the window/skylight geometry itself and the EnergyPlus window construction to be assigned. Honeybee zones without windows do not require the Add Honeybee Glazing component. After creating the Honeybee surface and glazing, the Create Honeybee Surfaces component and the Add Honeybee Glazing component were connected to the Create Honeybee Zones component. Besides the Honeybee surface geometry, the Create Honeybee Zones component only required a zone name to be assigned, as shown in Figure 190. All other zones, no matter the type, were created using this method. And for simplicity reasons the zones were split into floors and the floors were then denoted with a colour, as shown in Figure 184 and Figure 185, which illustrates the full Honeybee simulation scripts.

5. Assigning the EnergyPlus constructions to the Honeybee surfaces

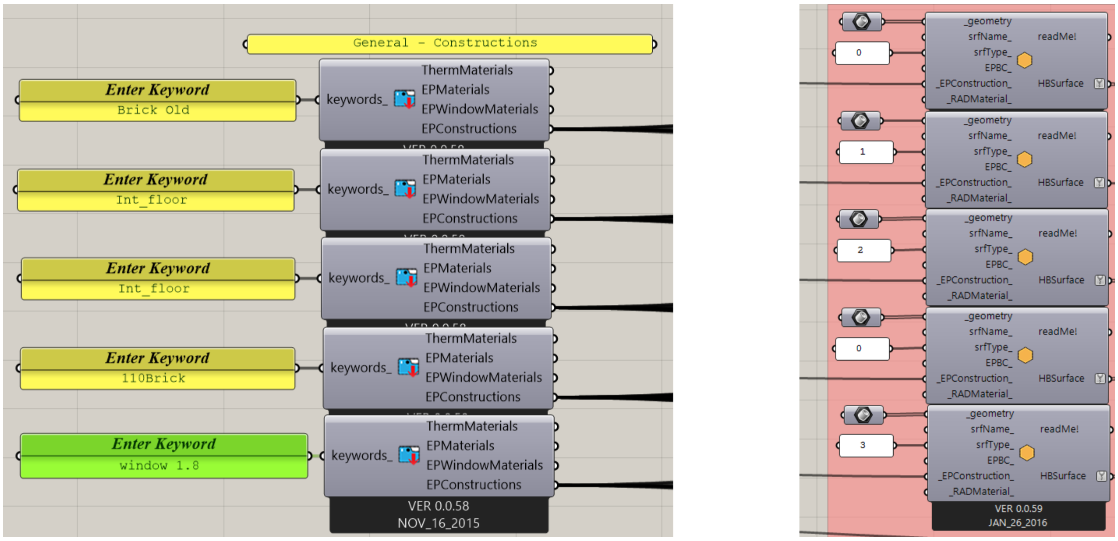

Figure 191: Assigning EnergyPlus constructions to surfaces

After the Honeybee zones were created, then the EnergyPlus constructions were assigned to each of the individual surfaces such as walls, roofs, floor slabs and windows. To assign the EnergyPlus constructions to the surfaces the Call From EnergyPlus Construction Library component was used together with a panel stating the keyword(s) for finding that specific construction type. If more than one construction came up in the library search with the chosen keyword(s), then the Item Selector component was used to select the correct one. The EnergyPlus Constructions output of the Call From EnergyPlus Construction Library component was then connected to the EnergyPlus Constructions input of the Create Honeybee Surfaces component, as shown in Figure 191. In addition to assigning EnergyPlus constructions through the detailed method as described in this section, it was also possible to assign the constructions on a building level by using the Set EnergyPlus Zone Constructions component, which would assign a set of general constructions affecting the entire building.

6. Converting the infiltration rate

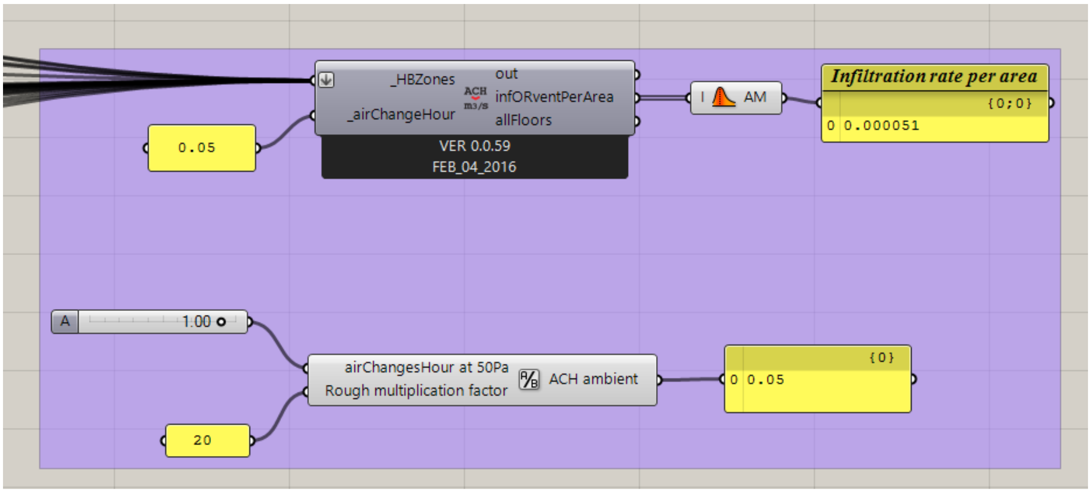

Figure 192: Converting the infiltration rate

After assigning EnergyPlus constructions to the individual surfaces of the building, the schedules, zone loads, and occupancy levels were specified. However, before this could be carried out, it was necessary to convert the infiltration rate stated in the given data from ac/h at 50Pa into l/s per m^2 floor area at ambient pressure. The infiltration rate was converted through two steps, the first was a simple division. Where the given ac/h at 50Pa was divided with a rough multiplication factor of 20, which are used for converting between 50Pa and ambient pressure. After the infiltration rate had been converted from 50Pa and ambient pressure, then the ambient infiltration rate (now 0.05 ac/h) was used as input for the Infiltration OR Ventilation Per Area Calculator component. Also the Honeybee zones were used as input for the Infiltration OR Ventilation Per Area Calculator component. As a result of the conversion by the Infiltration OR Ventilation Per Area Calculator component, the component would output the infiltration rate in l/s per m^2 floor area for each of the zones. The Average component was then used to calculate the average infiltration rate per m^2 floor area for the building (0.000051 l/s per m2 at ambient pressure), as shown in Figure 192.

7. Assigning schedules, zone loads, occupancy levels as well as ventilation- and infiltration rate.

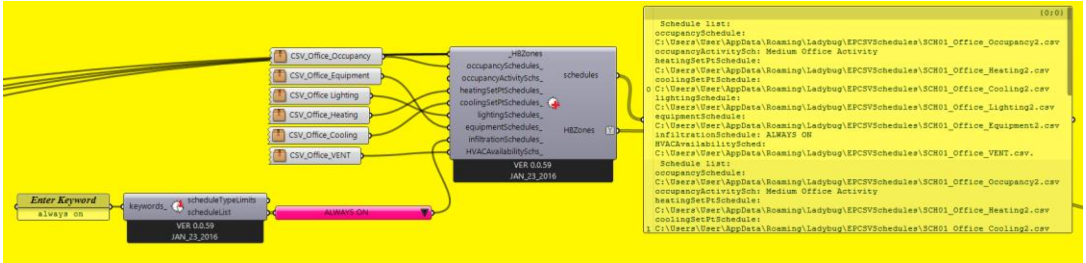

Figure 193: Assigning schedules

The first step of assigning the schedules, zone loads, occupancy levels, ventilation rate and infiltration rate, were to assign the schedules which involved using a Grasshopper function called "cluster". A cluster is a Grasshopper script which have been compressed into a single component. For the purpose of this study, the schedules were placed within clusters for simplicity when working with the script. The cluster components are shown in Figure 193, containing a small cardboard box and the text starting with "CSV". To illustrate how the cluster works, the content of the occupancy schedule for an office is shown in Figure 194. The main component for creating the schedules was the Create CSV Schedule component, to which a panel containing the hourly occupancy levels through the entire year was connected to values input. Besides the values input, specifying the name of the schedule was also required. The final component required to create the cluster was the Cluster Output component (the arrow on the right side of the Create CSV Schedule component). After the clusters had been created, it was simply to use them as input for the Set EnergyPlus Zone Schedules component. Schedules was also imported from the EnergyPlus schedules library using the Call From EnergyPlus Schedule Library component, as shown in Figure 193.

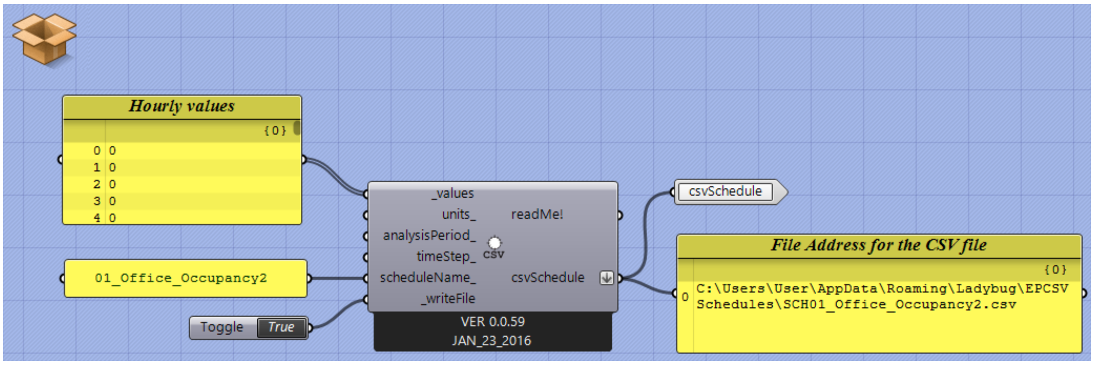

Figure 194: A cluster component

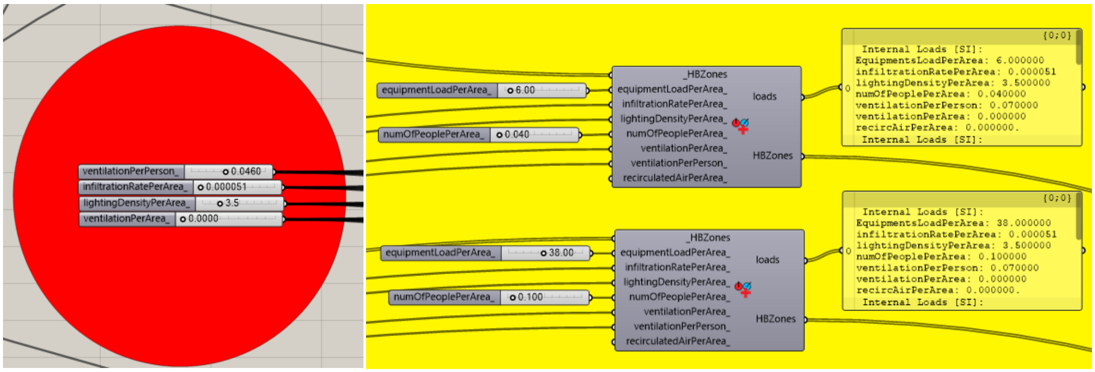

Figure 195: Assigning zone loads, occupancy levels as well as ventilation- and infiltration rate.

After the schedules were assigned, the zone loads, occupancy levels, ventilation rate and infiltration rate could be assigned using the Set EnergyPlus Zone Loads component. The Set EnergyPlus Zone Loads component used the Honeybee zones as well as number sliders as input. The number slider component is a native Grasshopper component, not a Honeybee component. The number sliders were used to specify the values for number of people per area (occupancy level), ventilation per person and ventilation per area (ventilation rate), infiltration rate per area as well as equipment- and lighting loads per area, for each of the zones, as shown in Figure 195.

8. Solve adjacencies and specifying ventilation parameters

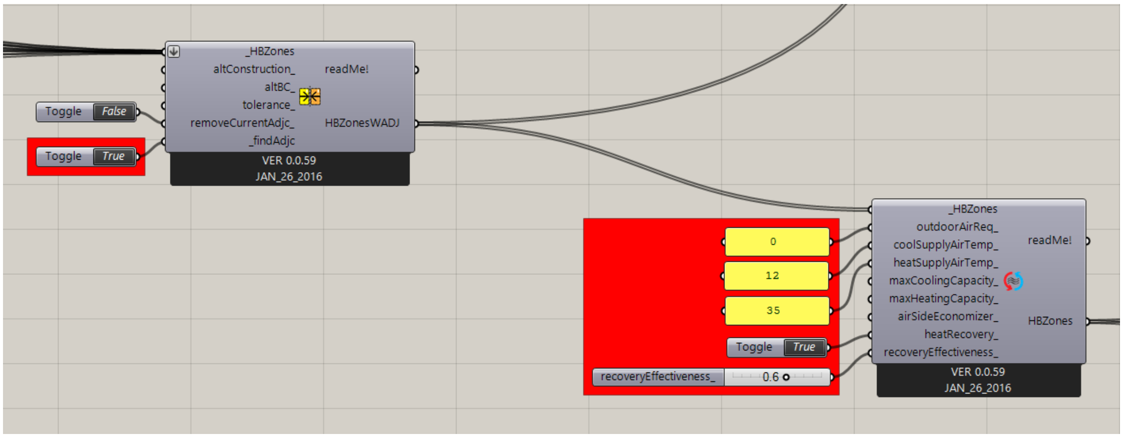

Figure 196: Solving adjacencies and specifying ventilation parameters

After all the constructions and zone specific settings were set, the Honeybee zones were passed through the Solve Adjacencies Component. As the name suggest this component solves the adjacencies between the zones, to ensure that interior walls and floors were actually considered as interior constructions instead of exterior. The modified Honeybee zone were then passed through the Set Ideal Air Loads Parameters component, where heat recovery efficiency, heating- and cooling supply air temperatures as well outdoor air requirements were specified, as shown in Figure 196.

9. Specifying simulation parameters and expected output

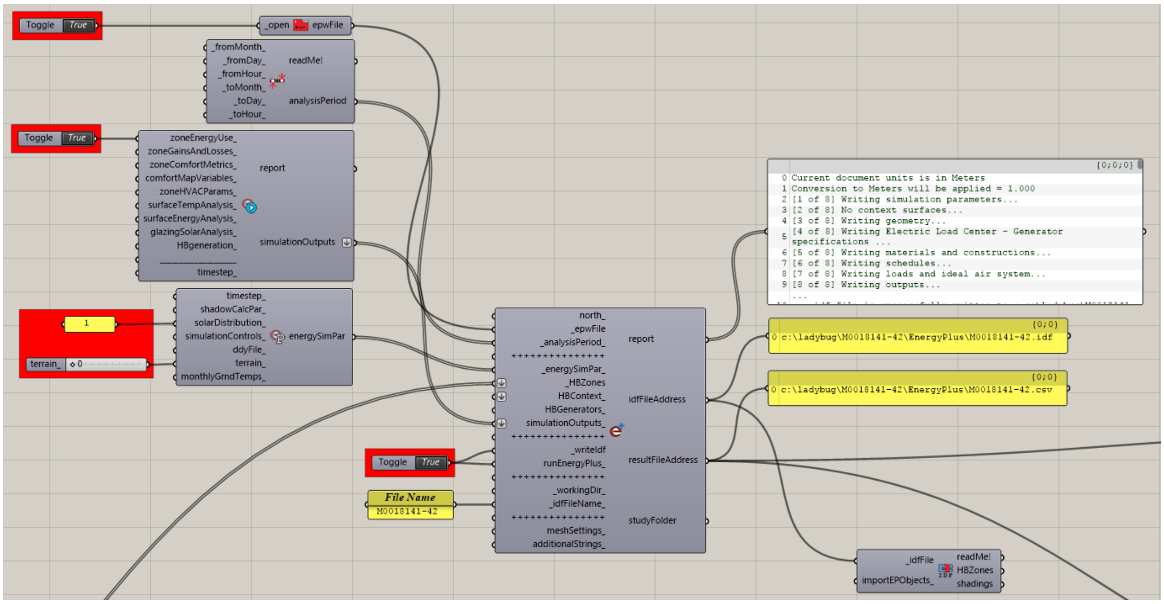

Figure 197: Specifying simulation parameters and expected output

After the adjacencies was solved and ventilation parameters had been specified, the Honeybee zones were connected to the Run Energy Simulation component. The Run Energy Simulation component was the main component for running the energy simulations. The Run Energy Simulation component required a weather file to be selected, an analysis period and simulation parameters to be specified, as well as the desired simulation output. The weather file was selected using the Open EPW Weather File component, which opens a “browse file” dialog, where the user can select any given EPW weather file located on the computer. The analysis period was specified using the Analysis Period component, which was left as default, and as a result the analysis period would start 1st of January and end at 31st of December. The simulation parameters were set using the Energy Simulation Parameters component, where the terrain type was set to “city” (0), and the solar distribution calculation settings were set to “Full Exterior”[5] (1), as shown in Figure 197.

[5] For more information regarding solar distribution and Full Exterior, see [166].

10. Results assessment

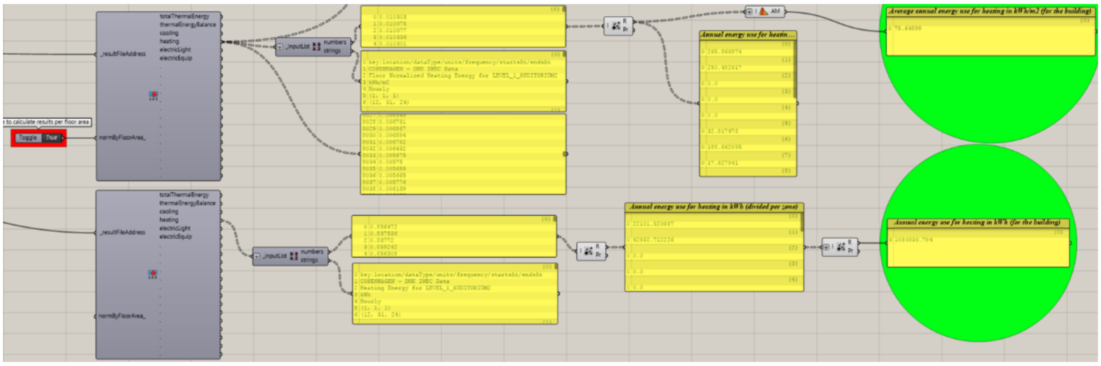

Figure 198: Results assessment in Honeybee

After the energy simulation was completed, the results were assessed using the Read EnergyPlus Result component. For the purpose of this study, two Read EnergyPlus Result components were used. Where the first was set to calculate the results per unit floor area (kWh/m^2) and the second to calculate the total result (kWh). The energy demand for space heating was selected in the Read EnergyPlus Result components, and the results were passed through the Separate Data component, which would separate text strings from numbers. The number would then be passed through the Mass Addition component, native in grasshopper, where all the values through the entire year would be summed up. For the results calculated per unit floor area, the result of the Mass Addition would come as annual energy demand for space heating per m^2 separated by zones, while for the total results, the result of the Mass Addition would come as total annual energy demand for space heating separated by zones. The results calculated per unit floor area, would then be passed through the Average component, which would result in the annual energy demand for space heating per m^2 for the entire building. In contrast to the results calculated per unit floor area, the total results would be passed through another Mass Addition component, resulting in the total energy demand for space heating for the entire building, as shown in Figure 198. On the illustration above, the method for the "per unit floor area results" is the upper half of the illustration, while the "total results" is the lower half, and the final results are shown in the two green circles.

11. Model visualization

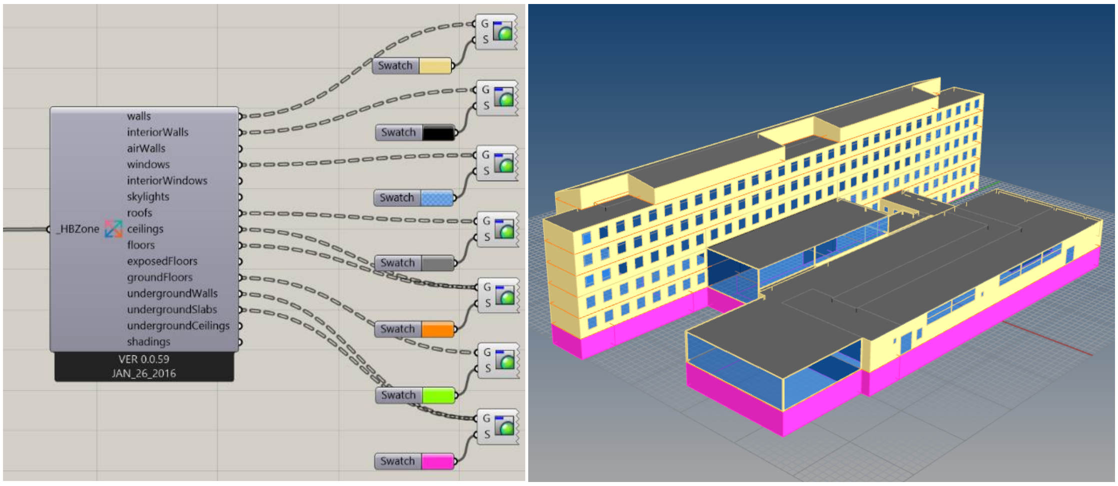

Figure 199: Visualizing the Honeybee model

While working with the script on the Grasshopper canvas, it was at times beneficial to visualize the model with colours in the Rhino window. This would help to detect errors such as areas where a wrong surface type had been assigned, or accident deletions of surfaces. In addition to spotting errors during the working process, the model was also visualized using the Import IDF component (shown in the lower right corner of Figure 197). Using the Import IDF component to Visualize the model allow the user to spot possible construction overlaps, due to geometry errors, such as window geometry overlapping wall or roof geometry, which would result in a “flicking” colour combination when the Rhino window is open. To visualize the model with colours in the Rhino window, the Decompose Based On Type component was used. The Honeybee zones was used as input, and each of the different construction categories were then connected to a Custom Preview component, native to Grasshopper. A Colour Swatch component, native to Grasshopper, was then connected to each of the Custom Preview components, and a colour would be selected based on HSV colour model in the Colour Swatch, as a result the construction type would be visualized with the given colour, as shown in Figure 199.

12. Error spotting

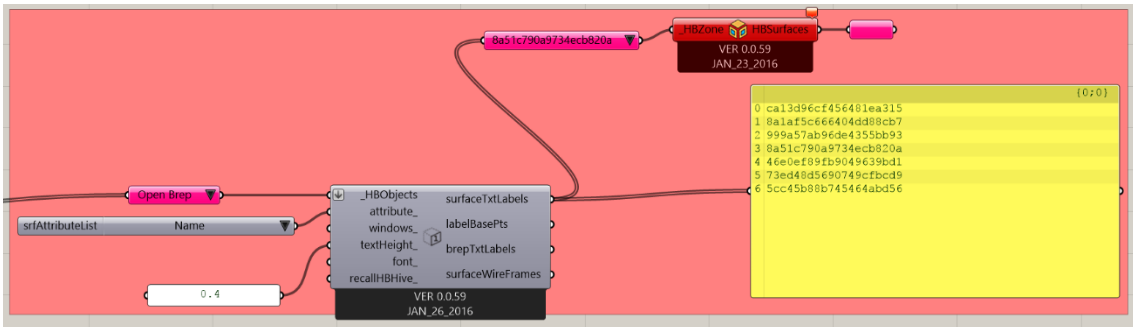

Figure 200: Error spotting in Honeybee

If an error occurred during the energy simulation, the Run Energy Simulation component would preview an error comment, to help find the sources of the error. Depending on the error, the error comment might inform the user what surface(s) are related to the error. However, in simulation projects with buildings containing a large number of zones, it can be very hard to find the few surfaces that is the source of the error. The Label Zone Surfaces component was therefore used. Placing an Item Selector component before the Label Zone Surfaces component, allows the user to check the surfaces of one zone at the time, making the process simpler. The Label Zone Surfaces component would then be set to label the name of the surfaces using the Surface Attribute List component, and as a result, all the surface names would appear in the panel (the yellow panel on the right). In addition to determine what zones contained the troublesome surfaces, the Label Zone Surfaces component would also visualize the zone surfaces in the Rhino window and label each surface with their respective name, as a result, making it easy to spot what surfaces in the building required attention, as shown in Figure 200.

12.4 Appendix D

Occupancy Schedules

Auditorium

```
Schedule:Compact,
Uni_ Auditorium _Occupancy,
Fraction,
Through: 31 Jan,
For: AllDays,
Until: 24:00, 0,
Through: 20 Jun,
For: Weekdays SummerDesignDay,
Until: 08:00, 0,
Until: 20:00, 1,
Until: 24:00, 0,
For: Weekends Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0,
Through: 20 Aug,
For: AllDays,
Until: 24:00, 0,
Through: 20 Dec,
For: Weekdays SummerDesignDay,
Until: 08:00, 0,
Until: 20:00, 1,
Until: 24:00, 0,
For: Weekends Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0,
Through: 31 Dec,
For: AllDays,
Until: 24:00, 0;
```

Cell Office

```
Schedule:Compact,
Uni_CellOffice_Occupancy,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 08:00, 0,
Until: 17:00, 1,
Until: 24:00, 0,
For: Weekends Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;
```

Circulation / Storage

```
Schedule:Compact,
Uni_Circulation_Occupancy,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 07:00, 0,
Until: 22:00, 1,
Until: 24:00, 0,
For: Weekends,
Until: 24:00, 0,
For: Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;
```

Classroom

Schedule:Compact,
Uni_Classroom_Occupancy,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 08:00, 0,
Until: 20:00, 1,
Until: 24:00, 0,
For: Weekends Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Workshop / Laboratory

Schedule:Compact,
Uni_Workshop_Occupancy,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 08:00, 0,
Until: 20:00, 1,
Until: 24:00, 0,
For: Weekends Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

HVAC Room

Schedule:Compact,
Uni_HVAC_Occupancy,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 09:00, 0,
Until: 17:00, 0.01,
Until: 24:00, 0,
For: Weekends Holidays,
Until: 12:00, 0,
Until: 14:00, 0.01,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

12.5 Appendix E

Heating Schedules

Auditorium

Schedule:Compact,
Uni_ Auditorium _Heating,
Temperature,
Through: 31 Jan,
For: AllDays,
Until: 24:00, 0.5,
Through: 20 Jun,
For: Weekdays SummerDesignDay
WinterDesignDay,
Until: 05:00, 0.5,
Until: 20:00, 1,
Until: 24:00, 0.5,
For: Weekends Holidays,
Until: 24:00, 0.5,
For: AllOtherDays,
Until: 24:00, 0.5,
Through: 20 Aug,
For: AllDays,
Until: 24:00, 0.5,
Through: 20 Dec,
For: Weekdays SummerDesignDay
WinterDesignDay,
Until: 05:00, 0.5,
Until: 20:00, 1,
Until: 24:00, 0.5,
For: Weekends,
Until: 24:00, 0.5,
For: Holidays,
Until: 24:00, 0.5,
For: AllOtherDays,
Until: 24:00, 0.5,
Through: 31 Dec,
For: AllDays,
Until: 24:00, 0.5;

Cell Office

Schedule:Compact,
Uni_CellOffice_Heating,
Temperature,
Through: 31 Dec,
For: Weekdays SummerDesignDay
WinterDesignDay,
Until: 05:00, 0.5,
Until: 17:00, 1,
Until: 24:00, 0.5,
For: Weekends Holidays,
Until: 24:00, 0.5,
For: AllOtherDays,
Until: 24:00, 0.5;

Circulation / Storage

Schedule:Compact,
Uni_Circulation_Heating,
Temperature,
Through: 31 Dec,
For: Weekdays SummerDesignDay
WinterDesignDay,
Until: 05:00, 0.5,
Until: 22:00, 1,
Until: 24:00, 0.5,
For: Weekends,
Until: 24:00, 0.5,
For: Holidays,
Until: 24:00, 0.5,
For: AllOtherDays,
Until: 24:00, 0;

Classroom

Schedule:Compact,
Uni_Classroom_Heating,
Temperature,
Through: 31 Dec,
For: Weekdays SummerDesignDay
WinterDesignDay,
Until: 05:00, 0.5,
Until: 20:00, 1,
Until: 24:00, 0.5,
For: Weekends Holidays,
Until: 24:00, 0.5,
For: AllOtherDays,
Until: 24:00, 0;

Workshop / Laboratory

Schedule:Compact,
Uni_Workshop_Heating,
Temperature,
Through: 31 Dec,
For: Weekdays SummerDesignDay
WinterDesignDay,
Until: 05:00, 0.5,
Until: 20:00, 1,
Until: 24:00, 0.5,
For: Weekends Holidays,
Until: 24:00, 0.5,
For: AllOtherDays,
Until: 24:00, 0;

HVAC Room

Schedule:Compact,
Uni_HVAC_Heating,
Temperature,
Through: 31 Dec,
For: AllDays,
Until: 24:00, 0;

12.6 Appendix F

Cooling Schedules

Auditorium

Schedule:Compact,
Uni_ Auditorium_Cooling,
Temperature,
Through: 31 Jan,
For: AllDays,
Until: 24:00, 0,
Through: 20 Jun,
For: Weekdays SummerDesignDay
WinterDesignDay,
Until: 05:00, 0,
Until: 20:00, 1,
Until: 24:00, 0,
For: Weekends Holidays,
Until: 24:00, 0,
For: AllOtherDays,
Until: 24:00, 0,
Through: 20 Aug,
For: AllDays,
Until: 24:00, 0,
Through: 20 Dec,
For: Weekdays SummerDesignDay
WinterDesignDay,
Until: 05:00, 0,
Until: 20:00, 1,
Until: 24:00, 0,
For: Weekends Holidays,
Until: 24:00, 0,
For: AllOtherDays,
Until: 24:00, 0,
Through: 31 Dec,
For: AllDays,
Until: 24:00, 0;

Cell Office

Schedule:Compact,
Uni_CellOffice_Cooling,
Temperature,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 05:00, 0,
Until: 17:00, 1,
Until: 24:00, 0,
For: Weekends Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Circulation / Storage

Schedule:Compact,
Uni_Circulation_Cooling,
Temperature,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 05:00, 0,
Until: 22:00, 1,
Until: 24:00, 0,
For: Weekends,
Until: 05:00, 0,
Until: 22:00, 0.25,
Until: 24:00, 0,
For: Holidays,
Until: 05:00, 0,
Until: 22:00, 0.25,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Classroom

Schedule:Compact,
Uni_Classroom_Cooling,
Temperature,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 07:00, 0,
Until: 20:00, 1,
Until: 24:00, 0,
For: Weekends Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Workshop / Laboratory

Schedule:Compact,
Uni_Workshop_Cooling,
Temperature,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 07:00, 0,
Until: 20:00, 1,
Until: 24:00, 0,
For: Weekends Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

HVAC Room

Schedule:Compact,
Uni_HVAC_Cooling,
Temperature,
Through: 31 Dec,
For: AllDays,
Until: 24:00, 0;

12.7 Appendix G

Lighting Schedules

Auditorium

Schedule:Compact,
Uni_ Auditorium_Lighting,
Fraction,
Through: 31 Jan,
For: AllDays,
Until: 24:00, 0,
Through: 20 Jun,
For: Weekdays SummerDesignDay,
Until: 08:00, 0,
Until: 20:00, 1,
Until: 24:00, 0,
For: Weekends Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0,
Through: 20 Aug,
For: AllDays,
Until: 24:00, 0,
Through: 20 Dec,
For: Weekdays SummerDesignDay,
Until: 08:00, 0,
Until: 20:00, 1,
Until: 24:00, 0,
For: Weekends Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0,
Through: 31 Dec,
For: AllDays,
Until: 24:00, 0;

Cell Office

Schedule:Compact,
Uni_CellOffice_Lighting,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 08:00, 0,
Until: 17:00, 1,
Until: 24:00, 0,
For: Weekends Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Circulation / Storage

Schedule:Compact,
Uni_Circulation_Lighting,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 07:00, 0,
Until: 22:00, 1,
Until: 24:00, 0,
For: Weekends,
Until: 07:00, 0,
Until: 22:00, 0.25,
Until: 24:00, 0,
For: Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Classroom

Schedule:Compact,
Uni_Classroom_Lighting,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 08:00, 0,
Until: 20:00, 1,
Until: 24:00, 0,
For: Weekends Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

HVAC Room

Schedule:Compact,
Uni_HVAC_Lighting,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 09:00, 0,
Until: 17:00, 0.01,
Until: 24:00, 0,
For: Weekends Holidays,
Until: 12:00, 0,
Until: 14:00, 0.01,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Workshop / Laboratory

Schedule:Compact,
Uni_Workshop_Lighting,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 08:00, 0,
Until: 20:00, 1,
Until: 24:00, 0,
For: Weekends,
Until: 24:00, 0,
For: Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

12.8 Appendix H

Equipment Schedules

Auditorium

Schedule:Compact,
Uni_ Auditorium_Equipment,
Fraction,
Through: 31 Jan,
For: AllDays,
Until: 24:00, 0.05475,
Through: 20 Jun,
For: Weekdays SummerDesignDay,
Until: 08:00, 0.05475,
Until: 20:00, 1,
Until: 24:00, 0.05475,
For: Weekends Holidays,
Until: 24:00, 0.05475,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0.05475,
Through: 20 Aug,
For: AllDays,
Until: 24:00, 0.05475,
Through: 20 Dec,
For: Weekdays SummerDesignDay,
Until: 08:00, 0.05475,
Until: 20:00, 1,
Until: 24:00, 0.05475,
For: Weekends Holidays,
Until: 24:00, 0.05475,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0.05475,
Through: 31 Dec,
For: AllDays,
Until: 24:00, 0.05475;

Cell Office

Schedule:Compact,
Uni_CellOffice_Equipment,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 08:00, 0.05457,
Until: 17:00, 1,
Until: 24:00, 0.05457,
For: Weekends Holidays,
Until: 24:00, 0.05457,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Circulation / Storage

Schedule:Compact,
Uni_Circulation_Equipment,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 07:00, 0.05475,
Until: 22:00, 1,
Until: 24:00, 0.05475,
For: Weekends,
Until: 24:00, 0.05475,
For: Holidays,
Until: 24:00, 0.05475,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Classroom

Schedule:Compact,
Uni_Classroom_Equipment,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 08:00, 0.05269,
Until: 20:00, 1,
Until: 24:00, 0.05269,
For: Weekends Holidays,
Until: 24:00, 0.05269,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

Workshop / Laboratory

Schedule:Compact,
Uni_Workshop_MechVent,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 08:00, .33,
Until: 20:00, 1,
Until: 24:00, .33,
For: Weekends Holidays,
Until: 24:00, 0.33,
For: WinterDesignDay AllOtherDays,
Until: 24:00, .33;

HVAC Room

Schedule:Compact,
Uni_HVAC_MechVent,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 09:00, 0,
Until: 17:00, 0.01,
Until: 24:00, 0,
For: Weekends Holidays,
Until: 12:00, 0,
Until: 14:00, 0.01,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;

12.9 Appendix I

Mechanical Ventilation Schedules

Auditorium

Schedule:Compact,
Uni_Auditorium_MechVent,
Fraction,
Through: 31 Jan,
For: AllDays,
Until: 24:00, 0.33,
Through: 20 Jun,
For: Weekdays SummerDesignDay,
Until: 08:00, 0.33,
Until: 20:00, 1,
Until: 24:00, 0.33,
For: Weekends Holidays,
Until: 24:00, 0.330,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0.33,
Through: 20 Aug,
For: AllDays,
Until: 24:00, 0.33,
Through: 20 Dec,
For: Weekdays SummerDesignDay,
Until: 08:00, 0.330,
Until: 20:00, 1,
Until: 24:00, 0.33,
For: Weekends Holidays,
Until: 24:00, 0.33,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0.33,
Through: 31 Dec,
For: AllDays,
Until: 24:00, 0.33;

Cell Office

Schedule:Compact,
Uni_CellOffice_MechVent,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 08:00, 0.33,
Until: 17:00, 1,
Until: 24:00, 0.33,
For: Weekends,
Until: 24:00, 0.33,
For: Holidays,
Until: 24:00, 0.33,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0.33;

Circulation / Storage

Schedule:Compact,
Uni_Circulation_MechVent,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 07:00, 0.33,
Until: 22:00, 1,
Until: 24:00, 0.33,
For: Weekends,
Until: 24:00, 0.33,
For: Holidays,
Until: 24:00, 0.33,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0.33;

Classroom

```
Schedule:Compact,
Uni_Classroom_MechVent,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 08:00, .33,
Until: 20:00, 1,
Until: 24:00, .33,
For: Weekends Holidays,
Until: 24:00, 0.33,
For: WinterDesignDay AllOtherDays,
Until: 24:00, .33;
```

Workshop / Laboratory

```
Schedule:Compact,
Uni_Workshop_Equipment,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 08:00, 0.0573,
Until: 20:00, 1,
Until: 24:00, 0.0573,
For: Weekends Holidays,
Until: 24:00, 0.0573,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;
```

HVAC Room

```
Schedule:Compact,
Uni_HVAC_Equipment,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 07:00, 0.22973,
Until: 20:00, 1,
Until: 24:00, 0.46081,
For: Weekends,
Until: 07:00, 0.22973,
Until: 24:00, 0.46081,
For: Holidays,
Until: 07:00, 0.22973,
Until: 24:00, 0.46081,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;
```

12.10 Appendix J

Table 32: Holiday Schedule

Name	Start Date	Number of days
New Year's Day	1st of January	1
Good Friday	1st Friday in April	1
Easter Sunday	1st Sunday in April	1
Easter Monday	2nd Monday in April	1
May Day	1st Monday in May	1
Spring Holiday	Last Monday in May	1
June Holiday	1st Monday in June	1
Summer Shutdown	3rd Monday in July	42
August Holiday	1st Monday in August	1
Late Summer Holiday	Last Monday in August	1
October Holiday	Last Monday in October	1
Christmas Day	25th of December	1
Boxing Day	26th of December	1
Post-Christmas Holiday	27th of December	5
Additional Holidays	No fixed date	5

12.11 Appendix K

Base Case Constructions

Table 33: Materials and thermal properties for slab on ground

Material / value	Thickness [m]	Bulk Density [kg/m³]	Specific Heat [J/(kg·K)]	Thermal Conductivity [W/(m·K)]	Thermal resistance [m²·K/W]
Interior surface resistance					0.17
Linoleum	0.003	1200	1400	0.170	0.02
Reinforced Concrete	0.150	2400	1000	2.500	0.06
Gravel	0.050	1840	840	0.600	0.08
Exterior surface resistance					0.04
∑R					0.37
U-value [W/(m²·K)]					2.70

Table 34: Materials and thermal properties for slab on ground (Exhibition hall)

Material / value	Thickness [m]	Bulk Density [kg/m³]	Specific Heat [J/(kg·K)]	Thermal Conductivity [W/(m·K)]	Thermal resistance [m²·K/W]
Interior surface resistance					0.17
Linoleum	0.003	1200	1400	0.170	0.02
Reinforced Concrete	0.150	2400	1000	2.500	0.06
EPS insulation	0.370	30	1500	0.040	9.25
Exterior surface resistance					0.04
∑R					9.54
U-value [W/(m²·K)]					0.10

Table 35: Materials and thermal properties for basement wall

Material / value	Thickness [m]	Bulk Density [kg/m³]	Specific Heat [J/(kg·K)]	Thermal Conductivity [W/(m·K)]	Thermal resistance [m²·K/W]
Interior surface resistance					0.13
EPS insulation	0.034	30	1500	0.040	0.85
Reinforced Concrete	0.200	2400	1000	2.500	0.08
Exterior surface resistance					0.04
∑R					1.10
U-value [W/(m²·K)]					0.91

Table 36: Materials and thermal properties for external wall – brick (Floor 1-5)

Material / value	Thickness [m]	Bulk Density [kg/m^3]	Specific Heat [J/(kg·K)]	Thermal Conductivity [W/(m·K)]	Thermal resistance [m^2·K/W]
Interior surface resistance					0.13
Solid Brick Masonry	0.395	1900	850	0.600	0.61
Gypsum Plaster	0.015	850	850	0.280	0.05
Exterior surface resistance					0.04
∑R					0.83
U-value [W/(m^2·K)]					1.20

Table 37: Materials and thermal properties for external wall – copper (Floor 6)

Material / value	Thickness [m]	Bulk Density [kg/m^3]	Specific Heat [J/(kg·K)]	Thermal Conductivity [W/(m·K)]	Thermal resistance [m^2·K/W]
Interior surface resistance					0.13
Copper Cladding	0.001	8900	380	300	0.00001
Plywood	0.015	450	1880	0.100	0.15
Stone wool	0.140	40	840	0.038	3.68
Gypsum Plaster	0.013	850	850	0.280	0.05
Exterior surface resistance					0.04
∑R					4.05
U-value [W/(m^2·K)]					0.25

Table 38: Materials and thermal properties for bitumen roof (Floor 1-5)

Material / value	Thickness [m]	Bulk Density [kg/m^3]	Specific Heat [J/(kg·K)]	Thermal Conductivity [W/(m·K)]	Thermal resistance [m^2·K/W]
Interior surface resistance					0.10
Asphalt paper	0.01	2100	1000	0.7	0.01
Stone wool	0.36	40	840	0.038	9.47
Reinforced Concrete	0.150	2400	1000	2.500	0.06
Exterior surface resistance					0.04
∑R					9.69
U-value [W/(m^2·K)]					0.10

Table 39: Materials and thermal properties for bitumen roof (Floor 6)

Material / value	Thickness [m]	Bulk Density [kg/m^3]	Specific Heat [J/(kg·K)]	Thermal Conductivity [W/(m·K)]	Thermal resistance [m^2·K/W]
Interior surface resistance					0.10
Asphalt paper	0.010	2100	1000	0.7	0.01
Stone wool	0.135	40	840	0.038	3.55
Metal Deck	0.120	7824	500	45.28	0.003
Gypsum Plaster	0.013	850	850	0.280	0.05
Exterior surface resistance					0.04
∑R					3.76
U-value [W/(m^2·K)]					0.27

Table 40: Materials and thermal properties for copper roof (Floor 6)

Material / value	Thickness [m]	Bulk Density [kg/m^3]	Specific Heat [J/(kg·K)]	Thermal Conductivity [W/(m·K)]	Thermal resistance [m^2·K/W]
Interior surface resistance					0.10
Copper Cladding	0.001	8900	380	300	0.00001
Plywood	0.015	450	1880	0.100	0.15
Stone wool	0.040	40	840	0.038	1.05
Gypsum Plaster	0.013	850	850	0.280	0.05
Exterior surface resistance					0.04
∑R					1.39
U-value [W/(m^2·K)]					0.72

12.12 Appendix L

Input for the Life Cycle Cost for the A-building

Reference Wall Construction

Running costs

POINT IN TIME MATERIAL MAINTENANCE 1

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Replace interior surface plaster					
Nordsjö Professional P6 Vapour permeable paint	m2	4135	7,142857	7,91831	0,1
Breaking down old interior plaster/render	m2	4135		0	0,54
LIP 350 Universal Render Grey	m2	4135	80,00	88,68507	0,23
Material container + crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563,074	
Material container 6m	md	5	1320	1463,304	
Building site electricity 19 kWh/day (3x800W power tools used 8h/d)	days	99		14,535	
Material Deliveries (assumption)	pcs	1		10000	
Transport cost (2 cars, 50km each way, 3 SEK/km) (assumption)	days	99		600	
4 persons' light crew trailer	days	99	110	121,942	
Heating and EL use in the crew trailers	day	99		40,8	
Waste container delivery	pcs	1	370	410,1685	
Waste container return	pcs	1	1418	1571,943	
Waste disposal (Cement render)	ton	79	915	1014,336	
Empty Waste container (each can hold max 10tons)	pcs	8	1418	1571,943	
Waste container	days	99	55	60,97099	
Maintenance interval	year	45			
Number of maintenances during the calculation period	pcs	1			

POINT IN TIME MATERIAL MAINTENANCE 2

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Small repairs for the interior surface plaster					
Repair of interior surface plaster (estimated to 100m2 per 5 years)	m2	100	19	21	0,31
Maintenance interval	year	5			
Number of maintenances during the calculation period	pcs	9			

ENERGY

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual energy use (FROM ENERGY SIMULATION TOOL)	kWh/year	1193310		0,912	

YEARLY MAINTENANCE

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual maintenance price (cleaning, small fixes etc.) (assumption)	SEK/year	1		8000	

COST FOR LOST FLOOR SPACE DUE TO THE INTERIOR LIGHT WALL

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual cost for lost space	m2	0		1149	

Wall Assembly H

Initial costs

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
General Construction Materials and Tasks					
SkamoPlus 100mm Calcium Silicate insulation board	m2	4135	599	664	0,07
SKALFLEX SALTBINDER/PRIMER (Silicate based)	m2	4135	26	29	0,10
SKALFLEX MULTISPARTEL (Vapour permeable adhesive)	m2	4135	37	41	0,05
Nordsjö Professional P6 Vapour permeable paint	m2	4135	7	8	0,10
LIP 350 Universal Render Grey	m2	4135	80	89	0,23
SKALTHERM GRUNDPUDS (Vapour permeable interior plaster)	m2	4135	186	206	0,23
Glass wool insulation 80mm (Ceiling hanging acc. to HEAT2 details)	m2	4640	48	53	0,10
SPIT ISO S Insulation anchors for ceiling hanging Glass wool	pcs	10000	2	2	
New Linoleum flooring	m2	9355	288	319	0,16
EPS insulation 40mm (in subfloor acc. to HEAT2 details)	m2	9355	40	44	0,07
EPS insulation 40mm (in window sills acc. to HEAT2 details)	m2	797	40	44	0,07
Wooden window revels	m	1982	189	209	0,11
Window board from natural stone grey 30mm thick	m	674	659	730	0,57
Breaking down old interior plaster/render	m2	4135		0	0,54
Cleaning the interior wall surfaces after plaster removal	m2	4135		0	0,04
Water repellent coating (Borup Vandtæt)	m2	4135	25	28	0,26

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Tools, Machinery and Other Materials					
Mixed small items (tools, bolts, screws etc.) (Assumption)	pcs	1		25000	

Material container 6m x3	md	8	1320	1463	
Sax lift 8m EL	days	80	999	1107	
4 persons' light crew trailer x2	days	156	220	244	
Material container transport costs (Delivery and pickup)	pcs	3	1410	1563	
Crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563	
MANITOU MRT 2145 (for application of water repellent coating)	days	60	3200	3547	
Fall security equipment (for application of water repellent coating) x2	days	60	198	219	
Shuttering spray 5L (for application of water repellent coating) x2	days	60	138	153	
Cement fixer 140L	days	140	239	265	
Dehumidifier BD 2420 50L x3	days	80	360	399	
Power drill SDS-PLUS 6-22 MM	days	40	156	173	
ALTO vacuum cleaner 450	days	150	289	320	
Fall pipe 1m pieces x20	days	150	580	643	
Erection and removal of fall pipe	m	50		0	0,77
Manitou transport costs (Delivery and pickup)	pcs	1	1500	1663	
Compressor M42 (for removal of existing plaster) x3	days	90	1800	1995	
Compressor hammer + usage (for removal of existing plaster) x3	days	90	630	698	
Waste container x2	days	156	110	122	
Waste container delivery x2	pcs	1	740	820	
Waste container return x 2	pcs	1	2836	3144	
Empty Waste container (each can hold max 10tons)	pcs	14	1418	1572	
Waste disposal (Mixed)	ton	20	1240	1375	
Waste disposal (Stones, concrete, brick, cement)	ton	118	275	305	
Building site electricity 50 kWh/day (8x800W power tools used 8h/d)	days	156		38	
Transport cost (4 cars, 50km each way, 3 SEK/km)	days	156		1200	
Material Deliveries	pcs	1		100000	
Establishing the crew trailers x2	pcs	2		0	3,00

Building site cleaning (1 hour per week 4 persons)	weeks	31		0	4,00
Heating and EL use in the crew trailers (2 pcs)	day	156		82	
Cleaning of crew trailers (1 time per week) x2	weeks	31	242	268	

Running costs

POINT IN TIME MATERIAL MAINTENANCE 1

Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Reapplying water repellent coating					
Water repellent coating (Borup Vandtæt)	m2	4135	25	28	0,26
Cleaning exterior wall surfaces	m2	4135		0	0,04
Shuttering spray 5L (for application of water repellent coating) x2	days	39	138	153	
MANITOU MRT 2145 (for application of water repellent coating)	days	39	3200	3547	
Fall security equipment (for application of water repellent coating) x2	days	39	198	219	
Material container 6m	md	2	1320	1463	
Material container + crew trailer + Manitou transport costs (Delivery and pickup)	pcs	3	1410	1563	
Material Deliveries (assumption)	pcs	1		2500	
Transport cost (2 cars, 50km each way, 3 SEK/km)	days	39		600	
4 persons' light crew trailer	days	39	110	122	
Heating and EL use in the crew trailers	day	39		41	
Maintenance interval	year	10			
Number of maintenances during the calculation period	pcs	4			

POINT IN TIME MATERIAL MAINTENANCE 2

Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Replace interior surface plaster					
Nordsjö Professional P6 Vapour permeable paint	m2	4135	7	8	0,10
Breaking down old interior plaster/render	m2	4135			0,54
SKALTHERM GRUNDPUDS (Vapour permeable interior plaster)	m2	4135	186	206	0,23
Material container + crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563	
Material container 6m	md	5	1320	1463	
Building site electricity 19 kWh/day (3x800W power tools used 8h/d)	days	99		15	
Material Deliveries (assumption)	pcs	1		10000	
Transport cost (2 cars, 50km each way, 3 SEK/km)	days	99		600	
4 persons’ light crew trailer	days	99	110	122	
Heating and EL use in the crew trailers	day	99		41	
Waste container delivery	pcs	1	370	410	
Waste container return	pcs	1	1418	1572	
Waste disposal (Cement render)	ton	79	915	1014	
Empty Waste container (each can hold max 10tons)	pcs	8	1418	1572	
Waste container	days	99	55	61	
Maintenance interval	year	45			
Number of maintenances during the calculation period	pcs	1			

POINT IN TIME MATERIAL MAINTENANCE 3

Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Small repairs for the interior surface plaster					
Repair of interior surface plaster (estimated to 100m2 per 5 years)	m2	100	19	21	0,31

Maintenance interval	year	5			
Number of maintenances during the calculation period	pcs	9			

ENERGY

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual energy use (FROM ENERGY SIMULATION TOOL)	kWh/year	916852		0,912	

YEARLY MAINTENANCE

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual maintenance price (cleaning, small fixes etc.) (assumption)	SEK/year	1		8000	

COST FOR LOST FLOOR SPACE DUE TO THE INTERIOR LIGHT WALL

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual cost for lost space	m2	212		1149	

Wall Assembly N

Initial costs

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
General Construction Materials and Tasks					
Aspen Aerogel Spaceloft insulation 30mm	m2	4135	796	882	0,07
Smart vapour retarder (Icopal Hygrodiode)	m2	4549	49	55	0,03
Gypsum Plasterboard	m2	4135	37	41	0,14
Nordsjö Professional P6 Vapour permeable paint	m2	4135	7	8	0,10
LIP 350 Universal Render Grey	m2	4135	80	89	0,23
Vapour retarder tape	m	20000	5	5	0,03
Glass wool insulation 80mm (Ceiling hanging acc. to HEAT2 details)	m2	4640	48	53	0,10
SPIT ISO S Insulation anchors for ceiling hanging Glass wool	pcs	10000	2	2	
Erection of wood battens for the air cavity	m2	4135	16	18	0,29
New Linoleum flooring	m2	9355	288	319	0,16
EPS insulation 40mm (in subfloor acc. to HEAT2 details)	m2	9355	40	44	0,07
EPS insulation 40mm (in window sills acc. to HEAT2 details)	m2	797	40	44	0,07
Wooden window revels	m	1982	189	209	0,11
Window board from natural stone grey 30mm thick	m	674	659	730	0,57
Water repellent coating (Borup Vandtæt)	m2	4135	25	28	0,26
Breaking down old interior plaster/render	m2	4135			0,54
Cleaning the interior wall surfaces after plaster removal	m2	4135			0,04

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Tools, Machinery and Other Materials					

Mixed small items (tools, bolts, screws etc.) (assumption)	pcs	1		25000	
Material container 6m x3	md	8	1320	1463	
Sax lift 8m EL	days	80	999	1107	
4 persons’ light crew trailer x2	days	150	220	244	
Material container transport costs (Delivery and pickup)	pcs	3	1410	1563	
Crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563	
MANITOU MRT 2145 (for application of water repellent coating)	days	60	3200	3547	
Fall security equipment (for application of water repellent coating) x2	days	60	198	219	
Shuttering spray 5L (for application of water repellent coating) x2	days	60	138	153	
Cement fixer 140L	days	140	239	265	
Dehumidifier BD 2420 50L x3	days	80	360	399	
Power drill SDS-PLUS 6-22 MM	days	40	156	173	
ALTO vacuum cleaner 450	days	140	289	320	
Fall pipe 1m pieces x20	days	140	580	643	
Erection and removal of fall pipe	m	50		0	0,77
Manitou transport costs (Delivery and pickup)	pcs	1	1500	1663	
Compressor M42 (for removal of existing plaster) x3	days	90	1800	1995	
Compressor hammer + usage (for removal of existing plaster) x3	days	90	630	698	
Waste container x2	days	150	110	122	
Waste container delivery x2	pcs	1	740	820	
Waste container return x 2	pcs	1	2836	3144	
Empty Waste container (each can hold max 10tons)	pcs	14	1418	1572	
Building site electricity 50 kWh/day (8x800W power tools used 8h/d) (Assumption based on common power tools)	days	150		38	
Waste disposal (Mixed)	ton	20	1240	1375	
Waste disposal (Stones, concrete, brick, cement)	ton	118	275	305	
Transport cost (4 cars, 50km each way, 3 SEK/km) (assumption)	days	150	1200	1200	

Drywall screw machine with band screws x3	days	60	438	486	
Chop Saw	days	60	117	130	
Material Deliveries (assumption)	pcs	1		100000	
Establishing the crew trailers x2	pcs	2		0	3,00
Building site cleaning (1 hour per week 4 persons)	weeks	34		0	4,00
Heating and EL use in the crew trailers (2 pcs)	day	150		82	
Cleaning of crew trailers (1 time per week) x2	weeks	34	242	268	

Running costs

POINT IN TIME MATERIAL MAINTENANCE 1

Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Reapplying water repellent coating					
Water repellent coating (Borup Vandtæt)	m2	4135	25	28	0,26
Cleaning exterior wall surfaces	m2	4135		0	0,04
Shuttering spray 5L (for application of water repellent coating) x2	days	39	138	153	
MANITOU MRT 2145 (for application of water repellent coating)	days	39	3200	3547	
Fall security equipment (for application of water repellent coating) x2	days	39	198	219	
Material container 6m	md	2	1320	1463	
Material container + crew trailer + Manitou transport costs (Delivery and pickup)	pcs	3	1410	1563	
Material Deliveries	pcs	1		2500	
Transport cost (2 cars, 50km each way, 3 SEK/km)	days	39		600	
4 persons' light crew trailer	days	39	110	122	
Heating and EL use in the crew trailers	day	39		41	

Maintenance interval	year	10			
Number of maintenances during the calculation period	pcs	4			

POINT IN TIME MATERIAL MAINTENANCE 2

Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Replacing interior surface plaster					
Gypsum Plasterboard	m2	4135	37	41	0,14
Removal of existing	m2	4135		0	0,05
Waste container	days	25	55	61	
Waste container delivery	pcs	1	370	410	
Waste container return	pcs	1	1418	1572	
Waste disposal (Gypsum)	ton	46	915	1014	
Empty Waste container (each can hold max 10tons)	pcs	5	1418	1572	
Material container + crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563	
Material container 6m	md	2	1320	1463	
Building site electricity 19 kWh/day (3x800W power tools used 8h/d)	days	25		15	
Material Deliveries	pcs	1		10000	
Transport cost (2 cars, 50km each way, 3 SEK/km)	days	25		600	
4 persons’ light crew trailer	days	25	110	122	
Heating and EL use in the crew trailers	day	25		41	
Maintenance interval	year	35			
Number of maintenances during the calculation period	pcs	1			

ENERGY

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual energy use (FROM ENERGY SIMULATION TOOL)	kWh/year	912845		0,912	

YEARLY MAINTENANCE

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual maintenance price (cleaning, small fixes etc.) (assumption)	SEK/year	1		8000	

COST FOR LOST FLOOR SPACE DUE TO THE INTERIOR LIGHT WALL

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual cost for lost space	m2	113		1149	

Wall Assembly O

Initial costs

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
General Construction Materials and Tasks					
Inner insulation layer (45mm)	m2	4135	14	16	0,07
Outer insulation layer (45mm)	m2	4135	14	16	0,07
Smart vapour retarder (Icopal Hygrodiode)	m2	4549	49	55	0,03
Erection of steel studs with Gypsum Plasterboard (45mm studs)	m2	4135	136	151	0,26
Nordsjö Professional P6 Vapour permeable paint	m2	4135	7	8	0,10
Vapour retarder tape	m	20000	5	5	0,03
Glass wool insulation 80mm (Ceiling hanging acc. to HEAT2 details)	m2	4640	48	53	0,10
SPIT ISO S Insulation anchors for ceiling hanging Glass wool	pcs	10000	2	2	
New Linoleum flooring	m2	9355	288	319	0,16
EPS insulation 40mm (in subfloor acc. to HEAT2 details)	m2	9355	40	44	0,07
EPS insulation 40mm (in window sills acc. to HEAT2 details)	m2	797	40	44	0,07
Wooden window revels	m	1982	189	209	0,11
Window board from natural stone grey 30mm thick	m	674	659	730	0,57
Breaking down old interior plaster/render	m2	4135		0	0,54
Cleaning the interior wall surfaces after plaster removal	m2	4135		0	0,04
Water repellent coating (Borup Vandtæt)	m2	4135	25	28	0,26

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Tools, Machinery and Other Materials					
Mixed small items (tools, bolts, screws etc.) (Assumption)	Pcs	1		25000	

Material container 6m x3	md	8	1320	1463	
Sax lift 8m EL	days	80	999	1107	
4 persons’ light crew trailer x2	days	148	220	244	
Material container transport costs (Delivery and pickup)	pcs	3	1410	1563	
Crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563	
MANITOU MRT 2145 (for application of water repellent coating)	days	60	3200	3547	
Fall security equipment (for application of water repellent coating) x2	days	60	198	219	
Shuttering spray 5L (for application of water repellent coating) x2	days	60	138	153	
Building site electricity 50 kWh/day (8x800W power tools used 8h/d)	days	148		38	
Dehumidifier BD 2420 50L x3	days	80	360	399	
Power drill SDS-PLUS 6-22 MM	days	40	156	173	
ALTO vacuum cleaner 450	days	140	289	320	
Fall pipe 1m pieces x20	days	135	580	643	
Erection and removal of fall pipe	m	50		0	0,77
Manitou transport costs (Delivery and pickup)	pcs	1	1500	1663	
Compressor M42 (for removal of existing plaster) x3	days	90	1800	1995	
Compressor hammer + usage (for removal of existing plaster) x3	days	90	630	698	
Waste container x2	days	148	110	122	
Waste container delivery x2	pcs	1	740	820	
Waste container return x 2	pcs	1	2836	3144	
Empty Waste container (each can hold max 10tons)	pcs	14	1418	1572	
Waste disposal (Mixed)	ton	20	1240	1375	
Waste disposal (Stones, concrete, brick, cement)	ton	118	275	305	
Angle Grinder Ø180 MM 220V	days	60	97	108	
Drywall screw machine with band screws x3	days	60	438	486	
Transport cost (4 cars, 50km each way, 3 SEK/km) (assumption)	days	148		1200	
Material Deliveries (assumption)	pcs	1		100000	

Establishing the crew trailers x2	pcs	2		0	3,00
Building site cleaning (1 hour per week 4 persons)	weeks	30		0	4,00
Heating and EL use in the crew trailers (2 pcs)	day	148		82	
Cleaning of crew trailers (1 time per week) x2	weeks	30	242	268	

Running costs

POINT IN TIME MATERIAL MAINTENANCE 1

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Reapplying water repellent coating					
Water repellent coating (Borup Vandtæt)	m2	4135	25	28	0,26
Cleaning exterior wall surfaces	m2	4135		0	0,04
Shuttering spray 5L (for application of water repellent coating) x2	days	39	138	153	
MANITOU MRT 2145 (for application of water repellent coating)	days	39	3200	3547	
Fall security equipment (for application of water repellent coating) x2	days	39	198	219	
Material container 6m	md	2	1320	1463	
Material container + crew trailer + Manitou transport costs (Delivery and pickup)	pcs	3	1410	1563	
Material Deliveries	pcs	1		2500	
Transport cost (2 cars, 50km each way, 3 SEK/km)	days	39		600	
4 persons’ light crew trailer	days	39	110	122	
Heating and EL use in the crew trailers	day	39		41	
Maintenance interval	year	10			
Number of maintenances during the calculation period	pcs	4			

POINT IN TIME MATERIAL MAINTENANCE 2

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Replacing interior surface plaster					
Gypsum Plasterboard	m2	4135	36,54	40,50655495	0,14
Removal of existing	m2	4135		0	0,05
Waste container	days	25	55	60,97098737	
Waste container delivery	pcs	1	370	410,1684605	
Waste container return	pcs	1	1418	1571,942911	
Waste disposal (Gypsum)	ton	46	915	1014,335517	
Empty Waste container (each can hold max 10tons)	pcs	5	1418	1571,942911	
Material container + crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563,074403	
Material container 6m	md	2	1320	1463,303697	
Building site electricity 19 kWh/day (3x800W power tools used 8h/d)	days	25		14,535	
Material Deliveries	pcs	1		10000	
Transport cost (2 cars, 50km each way, 3 SEK/km)	days	25		600	
4 persons' light crew trailer	days	25	110	121,9419747	
Heating and EL use in the crew trailers	day	25		40,8	
Maintenance interval	year	35			
Number of maintenances during the calculation period	pcs	1			

ENERGY

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual energy use (FROM ENERGY SIMULATION TOOL)	kWh/year	930255		0,912	

YEARLY MAINTENANCE

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual maintenance price (cleaning, small fixes etc.) (assumption)	SEK/year	1		8000	

COST FOR LOST FLOOR SPACE DUE TO THE INTERIOR LIGHT WALL

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual cost for lost space	m2	110		1149	

Reference Roof Construction

Running costs

POINT IN TIME MATERIAL MAINTENANCE 1

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Repairing holes and bumps in the bitumen felt roofing					
Waste disposal (Mixed)	ton	0,3	1240	1375	
Removal of bitumen felt roofing and put into depot for recycling (assumption)	m2	50		0	0,14
Fall security equipment (for roof in areas without railings) x2	days	4	198	219	
Bitumen felt roofing 2 layers (PF 3500 SBS and PF 5000 SBS) (assumption)	m2	50	249	276	0,20
Firefighting equipment (1 CO2 extinguishers, 1 powder extinguisher, 1 blankets)	md	1	334	370	
Bitumen felt burner	days	4	195	216	
Maintenance interval	year	5			
Number of maintenances during the calculation period	pcs	9			

POINT IN TIME MATERIAL MAINTENANCE 2

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Reapplying bitumen felt roofing					
Bitumen felt roofing 2 layers (PF 3500 SBS and PF 5000 SBS)	m2	3347	249	276	0,20
Removal of bitumen felt roofing and put into depot for recycling	m2	3347		0	0,14
Waste container	days	36	55	61	
Waste container delivery	pcs	1	370	410	
Waste container return	pcs	1	1418	1572	

Waste disposal (Mixed)	ton	12	1240	1375	
Empty Waste container (each can hold max 10tons)	pcs	2	1418	1572	
Fall security equipment (for roof in areas without railings) x4	days	36	396	439	
Roof fall security fencing 3m x20	days	36	640	709	
Firefighting equipment (5 CO2 extinguishers, 5 powder extinguisher, 5 blankets)	md	2	1670	1851	
Bitumen felt burner x4	days	36	780	865	
Material container + crew trailer + Manitou transport costs (Delivery and pickup)	pcs	3	1410	1563	
Material container 6m	md	2	1320	1463	
Building site electricity 19 kWh/day (3x800W power tools used 8h/d)	days	36		15	
Material Deliveries (assumption)	pcs	1		10000	
Transport cost (2 cars, 50km each way, 3 SEK/km) (assumption)	days	36		600	
4 persons’ light crew trailer	days	36	110	122	
Heating and EL use in the crew trailers	day	36		41	
MANITOU MRT 2145 (for lifting materials to the roof spaces)	days	15	3200	3547	
Exterior mini lift / elevator x2	days	36	398	441	
Maintenance interval	year	18			
Number of maintenances during the calculation period	pcs	2			

POINT IN TIME MATERIAL MAINTENANCE 3

Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Changing interior gypsum boards					
Gypsum Plasterboard	m2	4262	37	41	0,14
Removal of existing	m2	4262		0	0,05
Waste container	days	26	55	61	
Waste container delivery	pcs	1	370	410	

Waste container return	pcs	1	1418	1572	
Waste disposal (Gypsum)	ton	26	915	1014	
Empty Waste container (each can hold max 10tons)	pcs	6	1418	1572	
Material container + crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563	
Material container 6m	md	2	1320	1463	
Building site electricity 19 kWh/day (3x800W power tools used 8h/d)	days	26		15	
Material Deliveries (assumption)	pcs	1		10000	
Transport cost (2 cars, 50km each way, 3 SEK/km) (assumption)	days	26		600	
4 persons' light crew trailer	days	26	110	122	
Heating and EL use in the crew trailers	day	26		41	
Maintenance interval	year	35			
Number of maintenances during the calculation period	pcs	1			

ENERGY

Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Annual energy use (FROM ENERGY SIMULATION TOOL)	kWh/year	1193310		0,912	

YEARLY MAINTENANCE

Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Annual maintenance price (cleaning, small fixes etc.) (assumption)	SEK/year	1		8000	

Modified Roof Construction

Initial costs

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
General Construction Materials and Tasks					
Removal of steel cladding and put into depot for recycling (7kg/m2)	m2	578			0,07
Removal of bitumen felt roofing and put into depot for recycling	m2	3347			0,14
Removal of roof beams and put into depot for recycling	m	1242			0,14
Removal of insulation, seal and put into depot for recycling (based on 150mm)	m2	6935	3	3	0,18
Removal of roof gutters and put into depot for recycling	m	140			0,06
Removal of interior gypsum boards and put into depot for recycling	m2	4262			0,05
Removal of plywood board and put into depot for recycling	m2	599			0,06
Removal of wood battens and put into depot for recycling	m	1048			0,01
Bitumen felt roofing 2 layers (PF 3500 SBS and PF 5000 SBS)	m2	3347	249	276	0,20
Ext. EPS insulation on concrete deck including vapour barrier and mechanical fixing	m2	3010	560	621	0,23
Gypsum Plasterboard (ceiling hanging)	m2	4840	40	44	0,14
Copper Cladding, cut length and fix into place, 0,7mm	m2	578	1810	2006	3,56
Wooden roof beams 100x225mm, cut length and fix into place	m	1242	100	111	0,20
Wooden int. cross-battens 45x95mm, cut length and fix into place	m	1928	17	19	0,14
Steel brackets for wood constructions, fix into place (Bjælkesko 100x140mm)	pcs	350	51	56	0,15
Steel brackets for wood constructions, fix into place (Vinkelbeslag93x93x40mm)	pcs	1950	15	17	0,04
Wind tensioning straps, fix into place	m	600	62	68	0,05
Wooden wall place (for roof beams) 100x200mm x2	m	280	94	104	0,12
Asphalt paper on wall plates, width 200mm	m	140	10	11	0,02

Anchors for fixing wall plates, M24 length 290mm (Placed every 1000mm)	pcs	140	75	83	0,25
Mineral wool insulation class 37, 95mm	m2	915	36	40	0,09
Mineral wool insulation class 37, 245mm x2	m2	1830	96	107	0,20
Vapour retarder (PE-foilie, Dafa ProFoil t=0,2mm)	m2	636	6	7	0,03
Smart vapour retarder (Icopal Hygrodiode)	m2	371	49	55	0,03
Cement boards (Eternit) in air cavity, 13mm	m2	578	503	557	0,33
Wood battens in the air cavity (wood spacing strips 25x50mm cc 800mm) x2	m	1418	7	8	0,02
Oriented strand board (OSB) 20mm	m2	578	80	89	0,18
Exterior EPS insulation 70mm	m2	578	263	291	0,20
Vapour retarder tape	m	20000	5	5	0,03
Installing new roof gutters, half round in zinc, 250mm	m	140	225	249	0,61
Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Tools, Machinery and Other Materials					
Mixed small items (tools, bolts, screws etc.) (Assumption)	pcs	1		25000,00	
Material container 6m x3	md	7	1320	1463,30	
Sax lift 8m EL (for interior roof work)	days	50	999	1107,45	
4 persons’ light crew trailer x2	days	135	220	243,88	
Material container transport costs (Delivery and pickup)	pcs	3	1410	1563,07	
Crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563,07	
MANITOU MRT 2145 (for lifting materials to the roof spaces)	days	20	3200	3547,40	
Fall security equipment (for roof in areas without railings) x4	days	50	396	438,99	
Roof fall security fencing 3m x20	days	120	640	709,48	
Exterior mini lift / elevator x2	days	120	398	441,21	
Bitumen felt burner x4	days	30	780	864,68	

Polystyrene cutter	days	30	445	493,31	
Round saw 230mm 220V x2	day	135	252	279,36	
Band Saw 220V x2	days	135	272	301,53	
Drilling/Screwing machine x6	days	135	642	711,70	
Power drill SDS-PLUS 6-22 MM	days	135	156	172,94	
ALTO vacuum cleaner 450	days	135	289	320,37	
Fall pipe 1m pieces x20	days	120	580	642,97	
Erection and removal of fall pipe	m	50		0,00	0,77
Manitou transport costs (Delivery and pickup)	pcs	2	1500	1662,85	
Construction saw Ø400mm 380V	days	135	214	237,23	
Drywall screw machine with band screws x3	days	40	438	485,55	
Waste container x2	days	135	110	121,94	
Waste container delivery x2	pcs	1	740	820,34	
Waste container return x 2	pcs	1	2836	3143,89	
Empty Waste container (each can hold max 10tons)	pcs	18	1418	1571,94	
Building site electricity 50 kWh/day (8x800W power tools used 8h/d)	days	135		38,25	
Waste disposal (Mixed)	ton	60	1240	1374,62	
Waste disposal (Clean wood waste)	ton	32	275	304,85	
Waste disposal (Gypsum)	ton	47	915	1014,34	
Waste disposal (Metals)	ton	37	3	3,33	
Firefighting equipment (5 CO2 extinguishers, 5 powder extinguisher, 5 blankets)	md	7	1670	1851,30	
Transport cost (4 cars, 50km each way, 3 SEK/km) (Assumption)	days	135		1200,00	
Common building site fencing 3,5m x15	days	135	75	83,14	
3" water hose for the pump, 6m x2	days	50	198	219,50	
Water pump (for pumping water away from roof areas if needed)	days	50	299	331,46	
Material Deliveries (Assumption)	pcs	1		100000,00	

Establishing the crew trailers x2	pcs	2		0,00	3,00
Building site cleaning (1 hour per week 4 persons)	weeks	27		0,00	4,00
Heating and EL use in the crew trailers (2 pcs)	day	135		81,6	
Cleaning of crew trailers (1 time per week) x2	weeks	27	242	268,27	

Running costs

POINT IN TIME MATERIAL MAINTENANCE 1

Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Repairing holes and bumps in the bitumen felt roofing					
Waste disposal (Mixed)	ton	0,3	1240	1374,62	
Removal of bitumen felt roofing and put into depot for recycling (Estimated quantity)	m2	50		0,00	0,14
Fall security equipment (for roof in areas without railings) x2	days	4	198	219,50	
Bitumen felt roofing 2 layers (PF 3500 SBS and PF 5000 SBS) (Estimated quantity)	m2	50	249	276,03	0,20
Firefighting equipment (1 CO2 extinguishers, 1 powder extinguisher, 1 blankets)	md	1	334	370,26	
Bitumen felt burner	days	4	195	216,17	
Maintenance interval	year	5			
Number of maintenances during the calculation period	pcs	9			

POINT IN TIME MATERIAL MAINTENANCE 2

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Reapplying bitumen felt roofing					
Bitumen felt roofing 2 layers (PF 3500 SBS and PF 5000 SBS)	m2	3347	249	276,03	0,20
Removal of bitumen felt roofing and put into depot for recycling	m2	3347		0,00	0,14
Waste container	days	36	55	60,97	
Waste container delivery	pcs	1	370	410,17	
Waste container return	pcs	1	1418	1571,94	
Waste disposal (Mixed)	ton	12	1240	1374,62	
Empty Waste container (each can hold max 10tons)	pcs	2	1418	1571,94	
Fall security equipment (for roof in areas without railings) x4	days	36	396	438,99	
Roof fall security fencing 3m x20	days	36	640	709,48	
Firefighting equipment (5 CO2 extinguishers, 5 powder extinguisher, 5 blankets)	md	2	1670	1851,30	
Bitumen felt burner x4	days	36	780	864,68	
Material container + crew trailer + Manitou transport costs (Delivery and pickup)	pcs	3	1410	1563,074	
Material container 6m	md	2	1320	1463,304	
Building site electricity 19 kWh/day (3x800W power tools used 8h/d)	days	36		14,535	
Material Deliveries (Assumption)	pcs	1		10000	
Transport cost (2 cars, 50km each way, 3 SEK/km)	days	36		600	
4 persons’ light crew trailer	days	36	110	121,942	
Heating and EL use in the crew trailers	day	36		40,8	
MANITOU MRT 2145 (for lifting materials to the roof spaces)	days	15	3200	3547,40	
Exterior mini lift / elevator x2	days	36	398	441,21	
Maintenance interval	year	18			
Number of maintenances during the calculation period	pcs	1			

POINT IN TIME MATERIAL MAINTENANCE 3

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Changing interior gypsum boards					
Gypsum Plasterboard	m2	4840,18	36,54	40,51	0,14
Removal of existing	m2	4840,18		0,00	0,05
Waste container	days	29	55	60,97	
Waste container delivery	pcs	1	370	410,17	
Waste container return	pcs	1	1418	1571,94	
Waste disposal (Gypsum)	ton	54	915	1014,34	
Empty Waste container (each can hold max 10tons)	pcs	6	1418	1571,94	
Material container + crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563,074	
Material container 6m	md	2	1320	1463,304	
Building site electricity 19 kWh/day (3x800W power tools used 8h/d)	days	29		14,535	
Material Deliveries (Assumption)	pcs	1		10000	
Transport cost (2 cars, 50km each way, 3 SEK/km)	days	29		600	
4 persons' light crew trailer	days	29	110	121,942	
Heating and EL use in the crew trailers	day	29		40,8	
Maintenance interval	year	35			
Number of maintenances during the calculation period	pcs	1			

ENERGY

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual energy use (FROM ENERGY SIMULATION TOOL)	kWh/year	1136362		0,912	

YEARLY MAINTENANCE

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual maintenance price (cleaning, small fixes etc.) (assumption)	SEK/year	1		8000	

12.13 Appendix M

Input for the Life Cycle Cost for the V-building

Reference Wall Construction

Running costs

POINT IN TIME MATERIAL MAINTENANCE 1

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Replace interior surface plaster					
Nordsjö Professional P6 Vapour permeable paint	m2	6815	7	8	0,10
Breaking down old interior plaster/render	m2	6815			0,54
LIP 350 Universal Render Grey	m2	6815	80	89	0,23
Material container + crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563	
Material container 6m	md	9	1320	1463	
Building site electricity 19 kWh/day (3x800W power tools used 8h/d)	days	164		15	
Material Deliveries (Assumption)	pcs	1		10000	
Transport cost (2 cars, 50km each way, 3 SEK/km) (Assumption)	days	164		600	
4 persons’ light crew trailer	days	164	110	122	
Heating and EL use in the crew trailers	day	164		41	
Waste container delivery	pcs	1	370	410	
Waste container return	pcs	1	1418	1572	
Waste disposal (Gypsum plaster)	ton	58	915	1014	
Empty Waste container (each can hold max 10tons)	pcs	6	1418	1572	
Waste container	days	164	55	61	
Maintenance interval	year	45			
Number of maintenances during the calculation period	pcs	1			

POINT IN TIME MATERIAL MAINTENANCE 2

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Small repairs for the interior surface plaster					
Repair of interior surface plaster (estimated to 150m2 per 5 years)	m2	150	19	21	0,31
Maintenance interval	year	5			
Number of maintenances during the calculation period	pcs	9			

ENERGY

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual energy use (FROM ENERGY SIMULATION TOOL)	kWh/year	1774116		0,912	

YEARLY MAINTENANCE

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual maintenance price (cleaning, small fixes etc.) (assumption)	SEK/year	1		15000	

COST FOR LOST FLOOR SPACE DUE TO THE INTERIOR LIGHT WALL

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual cost for lost space	m2	0		1149	

Wall Assembly H

Initial costs

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
General Construction Materials and Tasks					
SkamoPlus 100mm Calcium Silicate insulation board	m2	6815	599	664	0,07
SKALFLEX SALTBINDER/PRIMER (Silicate based)	m2	6815	26	29	0,10
SKALFLEX MULTISPARTEL (Vapour permeable adhesive)	m2	6815	37	41	0,05
Nordsjö Professional P6 Vapour permeable paint	m2	6815	7	8	0,10
LIP 350 Universal Render Grey	m2	6815	80	89	0,23
SKALTHERM GRUNDPUDS (Vapour permeable interior plaster)	m2	6815	186	206	0,23
Glass wool insulation 80mm (Ceiling hanging acc. to HEAT2 details)	m2	6980	48	53	0,10
SPIT ISO S Insulation anchors for ceiling hanging Glass wool	pcs	14000	2	2	
New Linoleum flooring	m2	13265	288	319	0,16
EPS insulation 40mm (in subfloor acc. to HEAT2 details)	m2	13265	40	44	0,07
EPS insulation 40mm (in window sills acc. to HEAT2 details)	m2	1476	40	44	0,07
Wooden window revels	m	3670	189	209	0,11
Window board from natural stone grey 30mm thick	m	1250	659	730	0,57
Breaking down old interior plaster/render	m2	6815		0	0,54
Cleaning the interior wall surfaces after plaster removal	m2	6815		0	0,04
Water repellent coating (Borup Vandtæt)	m2	6815	25	28	0,26
Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Tools, Machinery and Other Materials					
Mixed small items (tools, bolts, screws etc.)	pcs	1		25000	

Material container 6m x3	md	8	1320	1463	
Sax lift 8m EL	days	180	999	1107	
4 persons’ light crew trailer x2	days	250	220	244	
Material container transport costs (Delivery and pickup)	pcs	3	1410	1563	
Crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563	
MANITOU MRT 2145 (for application of water repellent coating)	days	96	3200	3547	
Fall security equipment (for application of water repellent coating) x2	days	96	198	219	
Shuttering spray 5L (for application of water repellent coating) x2	days	96	138	153	
Cement fixer 140L	days	224	239	265	
Dehumidifier BD 2420 50L x3	days	150	360	399	
Power drill SDS-PLUS 6-22 MM	days	80	156	173	
ALTO vacuum cleaner 450	days	250	289	320	
Fall pipe 1m pieces x20	days	240	580	643	
Erection and removal of fall pipe	m	50		0	0,77
Manitou transport costs (Delivery and pickup)	pcs	1	1500	1663	
Compressor M42 (for removal of existing plaster) x3	days	155	1800	1995	
Compressor hammer + usage (for removal of existing plaster) x3	days	155	630	698	
Waste container x2	days	250	110	122	
Waste container delivery x2	pcs	1	740	820	
Waste container return x 2	pcs	1	2836	3144	
Empty Waste container (each can hold max 10tons)	pcs	23	1418	1572	
Waste disposal (Mixed)	ton	35	1240	1375	
Waste disposal (Stones, concrete, brick, cement)	ton	194	275	305	
Building site electricity 50 kWh/day (8x800W power tools used 8h/d) (Assumption)	days	250		38	
Transport cost (4 cars, 50km each way, 3 SEK/km) (Assumption)	days	250		1200	
Material Deliveries	pcs	1		150000	
Establishing the crew trailers x2	pcs	2		0	3,00

Building site cleaning (1 hour per week 4 persons)	weeks	50		0	4,00
Heating and EL use in the crew trailers (2 pcs)	day	250	204	82	
Cleaning of crew trailers (1 time per week) x2	weeks	50	242	268	

Running costs

POINT IN TIME MATERIAL MAINTENANCE 1

Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Reapplying water repellent coating					
Water repellent coating (Borup Vandtæt)	m2	6815	25	28	0,26
Cleaning exterior wall surfaces	m2	6815			0,04
Shuttering spray 5L (for application of water repellent coating) x2	days	64	138	153	
MANITOU MRT 2145 (for application of water repellent coating)	days	64	3200	3547	
Fall security equipment (for application of water repellent coating) x2	days	64	198	219	
Material container 6m	md	4	1320	1463	
Material container + crew trailer + Manitou transport costs (Delivery and pickup)	pcs	3	1410	1563	
Material Deliveries (Assumption)	pcs	1		2500	
Transport cost (2 cars, 50km each way, 3 SEK/km)	days	64		600	
4 persons' light crew trailer	days	64	110	122	
Heating and EL use in the crew trailers	day	64		41	
Maintenance interval	year	10			
Number of maintenances during the calculation period	pcs	4			

POINT IN TIME MATERIAL MAINTENANCE 2

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Replace interior surface plaster					
Nordsjö Professional P6 Vapour permeable paint	m2	6815	7	8	0,10
Breaking down old interior plaster/render	m2	6815			0,54
SKALTHERM GRUNDPUDS (Vapour permeable interior plaster)	m2	6815	186	206	0,23
Material container + crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563	
Material container 6m	md	9	1320	1463	
Building site electricity 19 kWh/day (3x800W power tools used 8h/d)	days	164		15	
Material Deliveries (Assumption)	pcs	1		10000	
Transport cost (2 cars, 50km each way, 3 SEK/km)	days	164		600	
4 persons' light crew trailer	days	164	110	122	
Heating and EL use in the crew trailers	day	164		41	
Waste container delivery	pcs	1	370	410	
Waste container return	pcs	1	1418	1572	
Waste disposal (Gypsum plaster)	ton	58	915	1014	
Empty Waste container (each can hold max 10tons)	pcs	6	1418	1572	
Waste container	days	164	55	61	
Maintenance interval	year	45			
Number of maintenances during the calculation period	pcs	1			

POINT IN TIME MATERIAL MAINTENANCE 3

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Small repairs for the interior surface plaster					
Repair of interior surface plaster (estimated to 150m2 per 5 years)	m2	150	19	21	0,31

Maintenance interval	year	5			
Number of maintenances during the calculation period	pcs	9			

ENERGY

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual energy use (FROM ENERGY SIMULATION TOOL)	kWh/year	1266704		0,912	

YEARLY MAINTENANCE

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual maintenance price (cleaning, small fixes etc.) (assumption)	SEK/year	1		15000	

COST FOR LOST FLOOR SPACE DUE TO THE INTERIOR LIGHT WALL

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual cost for lost space	m2	325		1149	

Wall Assembly N

Initial costs

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
General Construction Materials and Tasks					
Aspen Aerogel Spaceloft insulation 30mm	m2	6815	796	882	0,07
Smart vapour retarder (Icopal Hygrodiode)	m2	7496,5	49	55	0,03
Gypsum Plasterboard	m2	6815	37	41	0,14
Nordsjö Professional P6 Vapour permeable paint	m2	6815	7	8	0,10
LIP 350 Universal Render Grey	m2	6815	80	89	0,23
Vapour retarder tape	m	30000	5	5	0,03
Glass wool insulation 80mm (Ceiling hanging acc. to HEAT2 details)	m2	6980	48	53	0,10
SPIT ISO S Insulation anchors for ceiling hanging Glass wool	pcs	14000	2	2	
Erection of wood battens for the air cavity	m2	6815	16	18	0,29
New Linoleum flooring	m2	13265	288	319	0,16
EPS insulation 40mm (in subfloor acc. to HEAT2 details)	m2	13265	40	44	0,07
EPS insulation 40mm (in window sills acc. to HEAT2 details)	m2	1476	40	44	0,07
Wooden window revels	m	3670	189	209	0,11
Window board from natural stone grey 30mm thick	m	1250	659	730	0,57
Breaking down old interior plaster/render	m2	6815			0,54
Cleaning the interior wall surfaces after plaster removal	m2	6815			0,04
Water repellent coating (Borup Vandtæt)	m2	6815	25	28	0,26
Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Tools, Machinery and Other Materials					

Mixed small items (tools, bolts, screws etc.)	pcs	1		25000	
Material container 6m x3	md	8	1320	1463	
Sax lift 8m EL	days	200	999	1107	
4 persons' light crew trailer x2	days	272	220	244	
Material container transport costs (Delivery and pickup)	pcs	3	1410	1563	
Crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563	
MANITOU MRT 2145 (for application of water repellent coating)	days	96	3200	3547	
Fall security equipment (for application of water repellent coating) x2	days	96	198	219	
Shuttering spray 5L (for application of water repellent coating) x2	days	96	138	153	
Cement fixer 140L	days	224	239	265	
Dehumidifier BD 2420 50L x3	days	150	360	399	
Power drill SDS-PLUS 6-22 MM	days	80	156	173	
ALTO vacuum cleaner 450	days	272	289	320	
Fall pipe 1m pieces x20	days	260	580	643	
Erection and removal of fall pipe	m	50			0,77
Manitou transport costs (Delivery and pickup)	pcs	1	1500	1663	
Compressor M42 (for removal of existing plaster) x3	days	155	1800	1995	
Compressor hammer + usage (for removal of existing plaster) x3	days	155	630	698	
Building site electricity 50 kWh/day (8x800W power tools used 8h/d) (Assumption)	days	272		38	
Waste container x2	days	272	110	122	
Waste container delivery x2	pcs	1	740	820	
Waste container return x 2	pcs	1	2836	3144	
Empty Waste container (each can hold max 10tons)	pcs	23	1418	1572	
Waste disposal (Mixed)	ton	35	1240	1375	
Waste disposal (Stones, concrete, brick, cement)	ton	194	275	305	
Transport cost (4 cars, 50km each way, 3 SEK/km) (Assumption)	days	272		1200	
Drywall screw machine with band screws x3	days	100	438	486	

Chop Saw	days	100	117	130	
Material Deliveries (Assumption)	pcs	1		150000	
Establishing the crew trailers x2	pcs	2			3,00
Building site cleaning (1 hour per week 4 persons)	weeks	55			4,00
Heating and EL use in the crew trailers (2 pcs)	day	272	204	82	
Cleaning of crew trailers (1 time per week) x2	weeks	55	242	268	

Running costs

POINT IN TIME MATERIAL MAINTENANCE 1

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Reapplying water repellent coating					
Water repellent coating (Borup Vandtæt)	m2	6815	25	28	0,26
Cleaning exterior wall surfaces	m2	6815			0,04
Shuttering spray 5L (for application of water repellent coating) x2	days	64	138	153	
MANITOU MRT 2145 (for application of water repellent coating)	days	64	3200	3547	
Fall security equipment (for application of water repellent coating) x2	days	64	198	219	
Material container 6m	md	4	1320	1463	
Material container + crew trailer + Manitou transport costs (Delivery and pickup)	pcs	3	1410	1563	
Material Deliveries (Assumption)	pcs	1		2500	
Transport cost (2 cars, 50km each way, 3 SEK/km)	days	64		600	
4 persons' light crew trailer	days	64	110	122	
Heating and EL use in the crew trailers	day	64		41	
Maintenance interval	year	10			
Number of maintenances during the calculation period	pcs	4			

POINT IN TIME MATERIAL MAINTENANCE 2

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Replace interior surface plaster					
Gypsum Plasterboard	m2	6815	37	41	0,14
Removal of existing	m2	6815			0,05
Waste container	days	41	55	61	
Waste container delivery	pcs	1	370	410	
Waste container return	pcs	1	1418	1572	
Waste disposal (Gypsum)	ton	58	915	1014	
Empty Waste container (each can hold max 10tons)	pcs	6	1418	1572	
Material container + crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563	
Material container 6m	md	3	1320	1463	
Building site electricity 19 kWh/day (3x800W power tools used 8h/d)	days	41		15	
Material Deliveries (Assumption)	pcs	1		10000	
Transport cost (2 cars, 50km each way, 3 SEK/km)	days	41		600	
4 persons’ light crew trailer	days	41	110	122	
Heating and EL use in the crew trailers	day	41		41	
Maintenance interval	year	35			
Number of maintenances during the calculation period	pcs	1			

ENERGY

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual energy use (FROM ENERGY SIMULATION TOOL)	kWh/year	1265770		0,912	

YEARLY MAINTENANCE

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual maintenance price (cleaning, small fixes etc.) (assumption)	SEK/year	1		15000	

COST FOR LOST FLOOR SPACE DUE TO THE INTERIOR LIGHT WALL

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual cost for lost space	m2	174		1149	

Wall Assembly O

Initial costs

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
General Construction Materials and Tasks					
Inner insulation layer (45mm)	m2	6815	14	16	0,07
Outer insulation layer (45mm)	m2	6815	14	16	0,07
Smart vapour retarder (Icopal Hygrodiode)	m2	7496,5	49	55	0,03
Erection of steel studs with Gypsum Plasterboard (45mm studs)	m2	6815	136	151	0,26
Nordsjö Professional P6 Vapour permeable paint	m2	6815	7	8	0,10
Vapour retarder tape	m	30000	5	5	0,03
Glass wool insulation 80mm (Ceiling hanging acc. to HEAT2 details)	m2	6980	48	53	0,10
SPIT ISO S Insulation anchors for ceiling hanging Glass wool	pcs	14000	2	2	
New Linoleum flooring	m2	13265	288	319	0,16
EPS insulation 40mm (in subfloor acc. to HEAT2 details)	m2	13265	40	44	0,07
EPS insulation 40mm (in window sills acc. to HEAT2 details)	m2	1476	40	44	0,07
Wooden window revels	m	3670	189	209	0,11
Window board from natural stone grey 30mm thick	m	1250	659	730	0,57
Breaking down old interior plaster/render	m2	6815		0	0,54
Cleaning the interior wall surfaces after plaster removal	m2	6815		0	0,04
Water repellent coating (Borup Vandtæt)	m2	6815	25	28	0,26
Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Tools, Machinery and Other Materials					
Mixed small items (tools, bolts, screws etc.)	pcs	1		25000	

Material container 6m x3	md	8	1320	1463	
Sax lift 8m EL	days	70	999	1107	
4 persons' light crew trailer x2	days	237	220	244	
Material container transport costs (Delivery and pickup)	pcs	3	1410	1563	
Crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563	
MANITOU MRT 2145 (for application of water repellent coating)	days	96	3200	3547	
Fall security equipment (for application of water repellent coating) x2	days	96	198	219	
Shuttering spray 5L (for application of water repellent coating) x2	days	96	138	153	
Building site electricity 50 kWh/day (8x800W power tools used 8h/d) (Assumption)	days	237		38	
Dehumidifier BD 2420 50L x3	days	150	360	399	
Power drill SDS-PLUS 6-22 MM	days	80	156	173	
ALTO vacuum cleaner 450	days	237	289	320	
Fall pipe 1m pieces x20	days	225	580	643	
Erection and removal of fall pipe	m	50		0	0,77
Manitou transport costs (Delivery and pickup)	pcs	1	1500	1663	
Compressor M42 (for removal of existing plaster) x3	days	155	1800	1995	
Compressor hammer + usage (for removal of existing plaster) x3	days	155	630	698	
Waste container x2	days	237	110	122	
Waste container delivery x2	pcs	1	740	820	
Waste container return x 2	pcs	1	2836	3144	
Empty Waste container (each can hold max 10tons)	pcs	23	1418	1572	
Waste disposal (Mixed)	ton	35	1240	1375	
Waste disposal (Stones, concrete, brick, cement)	ton	194	275	305	
Angle Grinder Ø180 MM 220V	days	90	97	108	
Drywall screw machine with band screws x3	days	90	438	486	
Transport cost (4 cars, 50km each way, 3 SEK/km) (Assumption)	days	237		1200	
Material Deliveries (Assumption)	pcs	1		150000	

Establishing the crew trailers x2	pcs	2		0	3,00
Building site cleaning (1 hour per week 4 persons)	weeks	47		0	4,00
Heating and EL use in the crew trailers (2 pcs)	day	237	204	82	
Cleaning of crew trailers (1 time per week) x2	weeks	47	242	268	

Running costs

POINT IN TIME MATERIAL MAINTENANCE 1

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Reapplying water repellent coating					
Water repellent coating (Borup Vandtæt)	m2	6815	25	28	0,26
Cleaning exterior wall surfaces	m2	6815		0	0,04
Shuttering spray 5L (for application of water repellent coating) x2	days	64	138	153	
MANITOU MRT 2145 (for application of water repellent coating)	days	64	3200	3547	
Fall security equipment (for application of water repellent coating) x2	days	64	198	219	
Material container 6m	md	4	1320	1463	
Material container + crew trailer + Manitou transport costs (Delivery and pickup)	pcs	3	1410	1563	
Material Deliveries (Assumption)	pcs	1		2500	
Transport cost (2 cars, 50km each way, 3 SEK/km)	days	64		600	
4 persons’ light crew trailer	days	64	110	122	
Heating and EL use in the crew trailers	day	64		41	
Maintenance interval	year	10			
Number of maintenances during the calculation period	pcs	4			

POINT IN TIME MATERIAL MAINTENANCE 2

Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Replace interior surface plaster					
Gypsum Plasterboard	m2	6815	37	41	0,14
Removal of existing	m2	6815			0,05
Waste container	days	41	55	61	
Waste container delivery	pcs	1	370	410	
Waste container return	pcs	1	1418	1572	
Waste disposal (Gypsum)	ton	58	915	1014	
Empty Waste container (each can hold max 10tons)	pcs	6	1418	1572	
Material container + crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563	
Material container 6m	md	3	1320	1463	
Building site electricity 19 kWh/day (3x800W power tools used 8h/d)	days	41		15	
Material Deliveries (Assumption)	pcs	1		10000	
Transport cost (2 cars, 50km each way, 3 SEK/km)	days	41		600	
4 persons’ light crew trailer	days	41	110	122	
Heating and EL use in the crew trailers	day	41		41	
Maintenance interval	year	35			
Number of maintenances during the calculation period	pcs	1			

ENERGY

Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Annual energy use (FROM ENERGY SIMULATION TOOL)	kWh/year	1280180		0,912	

YEARLY MAINTENANCE

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual maintenance price (cleaning, small fixes etc.) (assumption)	SEK/year	1		15000	

COST FOR LOST FLOOR SPACE DUE TO THE INTERIOR LIGHT WALL

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Annual cost for lost space	m2	168		1149	

Reference Roof Construction

Running costs

POINT IN TIME MATERIAL MAINTENANCE 1

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Repairing holes and bumps in the bitumen felt roofing					
Waste disposal (Mixed)	ton	0,6	1240	1375	
Removal of bitumen felt roofing and put into depot for recycling	m2	100		0	0,14
Fall security equipment (for roof in areas without railings) x2	days	8	198	219	
Bitumen felt roofing 2 layers (PF 3500 SBS and PF 5000 SBS)	m2	100	249	276	0,20
Firefighting equipment (1 CO2 extinguishers, 1 powder extinguisher, 1 blankets)	md	1	334	370	
Bitumen felt burner	days	8	195	216	
Maintenance interval	year	5			
Number of maintenances during the calculation period	pcs	9			

POINT IN TIME MATERIAL MAINTENANCE 2

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Reapplying bitumen felt roofing					
Bitumen felt roofing 2 layers (PF 3500 SBS and PF 5000 SBS)	m2	6125	249	276	0,20
Removal of bitumen felt roofing and put into depot for recycling	m2	6125		0	0,14
Waste container	days	66	55	61	
Waste container delivery	pcs	1	370	410	
Waste container return	pcs	1	1418	1572	
Waste disposal (Mixed)	ton	21	1240	1375	
Empty Waste container (each can hold max 10tons)	pcs	3	1418	1572	

Fall security equipment (for roof in areas without railings) x4	days	66	396	439	
Roof fall security fencing 3m x20	days	66	640	709	
Firefighting equipment (5 CO2 extinguishers, 5 powder extinguisher, 5 blankets)	md	4	1670	1851	
Bitumen felt burner x4	days	66	780	865	
Material container + crew trailer + Manitou transport costs (Delivery and pickup)	pcs	3	1410	1563	
Material container 6m	md	4	1320	1463	
Building site electricity 19 kWh/day (3x800W power tools used 8h/d)	days	66		15	
Material Deliveries	pcs	1		10000	
Transport cost (2 cars, 50km each way, 3 SEK/km)	days	66		600	
4 persons' light crew trailer	days	66	110	122	
Heating and EL use in the crew trailers	day	66		41	
MANITOU MRT 2145 (for lifting materials to the roof spaces)	days	25	3200	3547	
Exterior mini lift / elevator x2	days	66	398	441	
Maintenance interval	year	18			
Number of maintenances during the calculation period	pcs	2			

POINT IN TIME MATERIAL MAINTENANCE 3

Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Changing interior gypsum boards					
Gypsum Plasterboard	m2	6982	37	41	0,14
Removal of existing	m2	6982			0,05
Material container + crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563	
Material container 6m	md	3	1320	1463	
Building site electricity 19 kWh/day (3x800W power tools used 8h/d)	days	41		15	
Material Deliveries	pcs	1		10000	
Transport cost (2 cars, 50km each way, 3 SEK/km)	days	41		600	

4 persons' light crew trailer	days	41	110	122	
Heating and EL use in the crew trailers	day	41		41	
Waste container	days	41	55	61	
Waste container delivery	pcs	1	370	410	
Waste container return	pcs	1	1418	1572	
Waste disposal (Gypsum)	ton	59	915	1014	
Empty Waste container (each can hold max 10tons)	pcs	6	1418	1572	
Maintenance interval	year	35			
Number of maintenances during the calculation period	pcs	1			

ENERGY

Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Annual energy use (FROM ENERGY SIMULATION TOOL)	kWh/year	1774116		0,912	

YEARLY MAINTENANCE

Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Annual maintenance price (cleaning, small fixes etc.) (assumption)	SEK/year	1		15000	

Modified Roof Construction

Initial costs

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
General Construction Materials and Tasks					
Removal of steel cladding and put into depot for recycling (7kg/m2)	m2	710		0	0,07
Removal of bitumen felt roofing and put into depot for recycling	m2	6125		0	0,14
Removal of roof beams and put into depot for recycling	m	1015		0	0,14
Removal of insulation, seal and put into depot for recycling (based on 150mm)	m2	12813	3	3	0,18
Removal of roof gutters and put into depot for recycling	m	121		0	0,06
Removal of interior gypsum boards and put into depot for recycling	m2	6982		0	0,05
Removal of plywood board and put into depot for recycling	m2	344		0	0,06
Removal of wood battens and put into depot for recycling	m	784		0	0,01
Bitumen felt roofing 2 layers (PF 3500 SBS and PF 5000 SBS)	m2	6125	249	276	0,20
Ext. EPS insulation on concrete deck including vapour barrier and mechanical fixing	m2	5978	560	621	0,23
Gypsum Plasterboard (ceiling hanging)	m2	7693	40	44	0,14
Copper Cladding, cut length and fix into place, 0,7mm	m2	710	1810	2006	3,56
Wooden roof beams 100x225mm, cut length and fix into place	m	1122	100	111	0,20
Wooden int. cross-battens 45x95mm, cut length and fix into place	m	1711	17	19	0,14
Steel brackets for wood constructions, fix into place (Bjælkesko 100x140mm)	pcs	310	51	56	0,15
Steel brackets for wood constructions, fix into place (Vinkelbeslag93x93x40mm)	pcs	1750	15	17	0,04
Wind tensioning straps, fix into place	m	520	62	68	0,05
Wooden wall place (for roof beams) 100x200mm x2	m	242	94	104	0,12
Asphalt paper on wall plates, width 200mm	m	121	10	11	0,02
Anchors for fixing wall plates, M24 length 290mm (Placed every 1000mm)	pcs	120	75	83	0,25
Mineral wool insulation class 37, 95mm	m2	857	36	40	0,09

Mineral wool insulation class 37, 245mm x2	m2	1714	96	107	0,20
Vapour retarder (PE-foilie, Dafa ProFoil t=0,2mm)	m2	781	6	7	0,03
Smart vapour retarder (Icopal Hygrodiode)	m2	162	49	55	0,03
Cement boards (Eternit) in air cavity, 13mm	m2	710	503	557	0,33
Wood battens in the air cavity (wood spacing strips 25x50mm cc 800mm) x2	m	1661	7	8	0,02
Oriented strand board (OSB) 20mm	m2	710	80	89	0,18
Exterior EPS insulation 70mm	m2	710	263	291	0,20
Vapour retarder tape	m	30000	5	5	0,03
Installing new roof gutters, half round in zinc, 250mm	m	121	225	249	0,61
Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Tools, Machinery and Other Materials					
Mixed small items (tools, bolts, screws etc.)	pcs	1		25000	
Material container 6m x3	md	10	1320	1463	
Sax lift 8m EL (for interior roof work)	days	80	999	1107	
4 persons' light crew trailer x2	days	196	220	244	
Material container transport costs (Delivery and pickup)	pcs	3	1410	1563	
Crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563	
MANITOU MRT 2145 (for lifting materials to the roof spaces)	days	30	3200	3547	
Fall security equipment (for roof in areas without railings) x4	days	70	396	439	
Roof fall security fencing 3m x20	days	170	640	709	
Exterior mini lift / elevator x2	days	160	398	441	
Bitumen felt burner x4	days	50	780	865	
Polystyrene cutter	days	50	445	493	
Round saw 230mm 220V x2	day	196	252	279	
Band Saw 220V x2	days	196	272	302	

Drilling/Screwing machine x6	days	196	642	712	
Power drill SDS-PLUS 6-22 MM	days	196	156	173	
ALTO vacuum cleaner 450	days	196	289	320	
Fall pipe 1m pieces x20	days	180	580	643	
Erection and removal of fall pipe	m	50		0	0,77
Manitou transport costs (Delivery and pickup)	pcs	2	1500	1663	
Construction saw Ø400mm 380V	days	196	214	237	
Drywall screw machine with band screws x3	days	60	438	486	
Building site electricity 50 kWh/day (8x800W power tools used 8h/d) (Assumption)	days	196		38	
Waste container x2	days	196	110	122	
Waste container delivery x2	pcs	1	740	820	
Waste container return x 2	pcs	1	2836	3144	
Empty Waste container (each can hold max 10tons)	pcs	26	1418	1572	
Waste disposal (Mixed)	ton	105	1240	1375	
Waste disposal (Clean wood waste)	ton	27	275	305	
Waste disposal (Gypsum)	ton	78	915	1014	
Waste disposal (Metals) (Assumption)	ton	45	3	3	
Firefighting equipment (5 CO2 extinguishers, 5 powder extinguisher, 5 blankets)	md	10	1670	1851	
Transport cost (4 cars, 50km each way, 3 SEK/km) (Assumption)	days	196		1200	
Common building site fencing 3,5m x15	days	196	75	83	
3" water hose for the pump, 6m x2	days	75	198	219	
Water pump (for pumping water away from roof areas if needed)	days	75	299	331	
Material Deliveries (Assumption)	pcs	1		150000	
Establishing the crew trailers x2	pcs	2			3,00
Building site cleaning (1 hour per week 4 persons)	weeks	39			4,00
Heating and EL use in the crew trailers (2 pcs)	day	196	204	82	
Cleaning of crew trailers (1 time per week) x2	weeks	39	242	268	

Running costs

POINT IN TIME MATERIAL MAINTENANCE 1

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Repairing holes and bumps in the bitumen felt roofing					
Waste disposal (Mixed)	ton	0,6	1240	1375	
Removal of bitumen felt roofing and put into depot for recycling (Estimated quantity)	m2	100			0,14
Fall security equipment (for roof in areas without railings) x2	days	8	198	219	
Bitumen felt roofing 2 layers (PF 3500 SBS and PF 5000 SBS) (Estimated quantity)	m2	100	249	276	0,20
Firefighting equipment (1 CO2 extinguishers, 1 powder extinguisher, 1 blankets)	md	1	334	370	
Bitumen felt burner	days	8	195	216	
Maintenance interval	year	5			
Number of maintenances during the calculation period	pcs	9			

POINT IN TIME MATERIAL MAINTENANCE 2

Description	Unit	Quantity	Cost/Unit [DKK]	Cost/Unit [SEK]	Man hours/unit
Reapplying bitumen felt roofing					
Bitumen felt roofing 2 layers (PF 3500 SBS and PF 5000 SBS)	m2	6125	249	276	0,20
Removal of bitumen felt roofing and put into depot for recycling	m2	6125			0,14
Waste container	days	66	55	61	
Waste container delivery	pcs	1	370	410	
Waste container return	pcs	1	1418	1572	
Waste disposal (Mixed)	ton	21	1240	1375	
Empty Waste container (each can hold max 10tons)	pcs	3	1418	1572	
Fall security equipment (for roof in areas without railings) x4	days	66	396	439	

Roof fall security fencing 3m x20	days	66	640	709	
Firefighting equipment (5 CO2 extinguishers, 5 powder extinguisher, 5 blankets)	md	4	1670	1851	
Bitumen felt burner x4	days	66	780	865	
Material container + crew trailer + Manitou transport costs (Delivery and pickup)	pcs	3	1410	1563	
Material container 6m	md	4	1320	1463	
Building site electricity 19 kWh/day (3x800W power tools used 8h/d)	days	66		15	
Material Deliveries (Assumption)	pcs	1		10000	
Transport cost (2 cars, 50km each way, 3 SEK/km)	days	66		600	
4 persons’ light crew trailer	days	66	110	122	
Heating and EL use in the crew trailers	day	66		41	
MANITOU MRT 2145 (for lifting materials to the roof spaces)	days	25	3200	3547	
Exterior mini lift / elevator x2	days	66	398	441	
Maintenance interval	year	18			
Number of maintenances during the calculation period	pcs	2			

POINT IN TIME MATERIAL MAINTENANCE 3

Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Changing interior gypsum boards					
Gypsum Plasterboard	m2	7693	37	41	0,14
Removal of existing	m2	7693			0,05
Material container + crew trailer transport costs (Delivery and pickup)	pcs	2	1410	1563	
Material container 6m	md	3	1320	1463	
Building site electricity 19 kWh/day (3x800W power tools used 8h/d)	days	46		15	
Material Deliveries (Assumption)	pcs	1		10000	
Transport cost (2 cars, 50km each way, 3 SEK/km)	days	46		600	
4 persons’ light crew trailer	days	46	110	122	

Heating and EL use in the crew trailers	day	46		41	
Waste container	days	46	55	61	
Waste container delivery	pcs	1	370	410	
Waste container return	pcs	1	1418	1572	
Waste disposal (Gypsum)	ton	66	915	1014	
Empty Waste container (each can hold max 10tons)	pcs	7	1418	1572	
Maintenance interval	year	35			
Number of maintenances during the calculation period	pcs	1			

ENERGY

Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Annual energy use (FROM ENERGY SIMULATION TOOL)	kWh/year	1710538		0,912	

YEARLY MAINTENANCE

Description	**Unit**	**Quantity**	**Cost/Unit [DKK]**	**Cost/Unit [SEK]**	**Man hours/unit**
Annual maintenance price (cleaning, small fixes etc.) (assumption)	SEK/year	1		15000	

12.14 Appendix N

Input for the Life Cycle Assessment for the A-building

Reference Building (Wall assemblies) Components	Functional Unit	GWP	AP	EP	ODP	POCP	Quantity
Building Heating	kWh	4,00E-02	4,40E-04	8,40E-05	4,92E-09	4,32E-05	1193310
Renovation and replacement works							
Replace interior cement based plaster 15mm (28,5kg/m2, 4135m2 = 117,85ton), after 45 years	ton	1,28E+03	2,65E+00	2,80E-01	2,80E-07	1,90E-01	117,85
Assumed building site electricity 19 kWh/day, 99 days (3x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	1881,00
Transport, material deliveries, assumed 100 km 12 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1200,00
Transport, delivery/pickup of material containers, cabins, machinery, 100 km 2 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	200,00
Transport, delivery/empty/pickup of waste containers, 100 km 12 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1200,00
Transport, 2 cars, 50km each way (total 200km), for 99 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	19800,00
Electricity and heating (EL) for crew trailers for 99 days, with 53 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	5247,00
Wall ID = H Components	Functional Unit	GWP	AP	EP	ODP	POCP	Quantity
Building Heating	kWh	4,00E-02	4,40E-04	8,40E-05	4,92E-09	4,32E-05	916852
Main construction work							

Calcium Silicate Insulation boards 100mm (density 259 kg/m3, 4135m2 = 107,1ton)	ton	2,04E+03	2,15E+00	3,40E-01	4,56E-06	2,20E-01	107,10
Primer and Adhesive (based on Sto-Primer/Adhesive), 0,3kg/m2, 4135m2 = 1240,5 kg	kg	3,90E-01	2,31E-03	2,23E-03	8,00E-07	3,74E-04	1240,50
Interior vapour permeable paint (based on StoSil Colour), 0,14L/m2, 4135m2 = 579L	L	7,04E-01	5,31E-03	1,96E-03	1,37E-06	4,48E-04	579,00
New interior cement based plaster 15mm (28,5kg/m2, 4135m2 = 117,85ton)	ton	1,28E+03	2,65E+00	2,80E-01	2,80E-07	1,90E-01	117,85
No data for capillary active plaster found, instead the data for wet room plasterboards was used, as this board is suggested as an alternative to the capillary active plaster.	m2	3,48E+00	1,41E-02	8,70E-04	0,00E+00	1,50E-03	4135,00
Isover Glass Wool 37, 80mm (Ceiling hanging)	m3	3,19E+01	8,86E-02	5,31E-02	3,38E-06	7,66E-02	371,20
Anchors PVC, SPIT ISO S length 120mm, (Based on Ejot PVC anchors 120mm)	pcs	8,36E-02	2,69E-04	2,46E-05	4,48E-09	3,35E-05	10000,00
EPS insulation on existing floor, 40mm	m3	5,60E+01	1,20E-01	1,30E-02	1,60E-06	2,90E-01	374,20
EPS insulation around windows, 40mm	m3	5,60E+01	1,20E-01	1,30E-02	1,60E-06	2,90E-01	31,88
Wooden window reveals, thickness 20mm (based on painted pine wood)	m2	1,72E+00	8,43E-02	1,67E-02	1,34E-06	6,89E-03	1982,00
Window board from natural stone grey 30mm thick, density 2700kg/m3, 674m2 = 54,59ton	ton	1,77E+02	1,06E+00	3,20E-01	2,20E-05	3,70E-02	54,59
Linoleum flooring (Based on ERFMI plain and decorative linoleum)	m2	2,60E+00	3,80E-02	1,20E-02	1,00E-08	2,30E-03	9355,00
Water repellent coating (Based on StoPrep Miral), 0,35kg/m2 wall = 1447kg	kg	7,56E-01	7,47E-03	9,58E-04	5,85E-07	2,68E-04	1447,00
Assumed building site electricity 50 kWh/day, 156 days (8x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	7800,00
Transport, material deliveries, assumed 100 km 20 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	2000,00

Transport, delivery/pickup of material containers, cabins, machinery, 100 km 7 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	700,00
Transport, delivery/empty/pickup of waste containers, 100 km 16 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1600,00
Transport, 4 cars, 50km each way (total 400km), for 156 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	62400,00
Electricity and heating (EL) for crew trailers for 156 days, with 106 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	16536,00
Renovation and replacement works							
Water repellent coating (Based on StoPrep Miral), 0,35kg/m2 wall = 1447kg (4 times in 50 years)	kg	7,56E-01	7,47E-03	9,58E-04	5,85E-07	2,68E-04	5788,00
Full replacement of wet room plasterboard every 45 years acc. to LCC	m2	3,48E+00	1,41E-02	8,70E-04	0,00E+00	1,50E-03	4135,00
Assumed building site electricity 19 kWh/day, 99 days (3x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	1881,00
Transport, material deliveries, assumed 100 km 15 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1500,00
Transport, delivery/pickup of material containers, cabins, machinery, 100 km 12 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1200,00
Transport, delivery/empty/pickup of waste containers, 100 km 12 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1200,00
Transport, 2 cars, 50km each way (total 200km), for 254 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	50800,00
Electricity and heating (EL) for crew trailers for 254 days, with 53 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	13462,00

Wall ID = N **Components**	Functional Unit	GWP	AP	EP	ODP	POCP	Quantity
Building Heating	kWh	4,00E-02	4,40E-04	8,40E-05	4,92E-09	4,32E-05	912845
Main construction work							
Gypsum Plasterboard 12,5mm	m2	2,10E+00	1,80E-03	4,40E-03	1,40E-07	2,50E-04	4135,00
Smart vapour retarder (Icopal Hygrodiode) (Assumed 2 times normal vapour retarder)	m2	6,28E-01	2,40E-03	1,77E-04	9,12E-09	1,25E-04	4548,50
Vapour retarder tape	m	1,33E-01	4,64E-04	7,11E-05	3,00E-09	6,18E-05	20000,00
Aspen Aerogel Spaceloft Insulation 30mm (values for 10mm, area multiplied by 3)	m2	1,27E+01	5,99E-02	6,36E-03	3,63E-06	4,37E-03	12405,00
Interior vapour permeable paint (based on StoSil Colour), 0,14L/m2 = 579L	L	7,04E-01	5,31E-03	1,96E-03	1,37E-06	4,48E-04	579,00
New interior cement based plater 10mm (19kg/m2, 4135m2 = 78,57ton)	ton	1,28E+03	2,65E+00	2,80E-01	2,80E-07	1,90E-01	78,57
Wood battens 25x25mm (assumed 2m per m2 wall, 4135m2 = 5,17m3)	m3	-6,07E+02	6,60E-06	8,99E-02	6,60E-06	2,65E-02	5,17
Isover Glass Wool 37, 80mm (Ceiling hanging)	m3	3,19E+01	8,86E-02	5,31E-02	3,38E-06	7,66E-02	371,20
Anchors PVC, SPIT ISO S length 120mm, (Based on Ejot PVC anchors 120mm)	pcs	8,36E-02	2,69E-04	2,46E-05	4,48E-09	3,35E-05	10000,00
EPS insulation on existing floor, 40mm	m3	5,60E+01	1,20E-01	1,30E-02	1,60E-06	2,90E-01	374,20
EPS insulation around windows, 40mm	m3	5,60E+01	1,20E-01	1,30E-02	1,60E-06	2,90E-01	31,88
Wooden window reveals, thickness 20mm (based on painted pine wood)	m2	1,72E+00	8,43E-02	1,67E-02	1,34E-06	6,89E-03	1982,00
Window board from natural stone grey 30mm thick, density 2700kg/m3, 674m2 = 54,59ton	ton	1,77E+02	1,06E+00	3,20E-01	2,20E-05	3,70E-02	54,59
Linoleum flooring (Based on ERFMI plain and decorative linoleum)	m2	2,60E+00	3,80E-02	1,20E-02	1,00E-08	2,30E-03	9355,00

Water repellent coating (Based on StoPrep Miral), 0,35kg/m2 wall = 1447kg	kg	7,56E-01	7,47E-03	9,58E-04	5,85E-07	2,68E-04	1447,00
Assumed building site electricity 50 kWh/day, 150 days (8x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	7500,00
Transport, material deliveries, assumed 100 km 20 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	2000,00
Transport, delivery/pickup of material containers, cabins, machinery, 100 km 7 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	700,00
Transport, delivery/empty/pickup of waste containers, 100 km 15 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1500,00
Transport, 4 cars, 50km each way (total 400km), for 150 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	60000,00
Electricity and heating (EL) for crew trailers for 150 days, with 106 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	15900,00
Renovation and replacement works							
Water repellent coating (Based on StoPrep Miral), 0,35kg/m2 wall = 1447kg (4 times in 50 years)	kg	7,56E-01	7,47E-03	9,58E-04	5,85E-07	2,68E-04	5788,00
Full replace of Gypsum Plasterboard 12,5mm	m2	2,10E+00	1,80E-03	4,40E-03	1,40E-07	2,50E-04	4135,00
Assumed building site electricity 19 kWh/day, 25 days (3x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	475,00
Transport, material deliveries, assumed 100 km 6 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	600,00
Transport, delivery/pickup of material containers, cabins, machinery, 100 km 12 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1200,00
Transport, delivery/empty/pickup of waste containers, 100 km 5 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	500,00

Transport, 2 cars, 50km each way (total 200km), for 180 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	36000,00
Electricity and heating (EL) for crew trailers for 180 days, with 53 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	9540,00

Wall ID = O **Components**	Functional Unit	GWP	AP	EP	ODP	POCP	Quantity
Building Heating	kWh	4,00E-02	4,40E-04	8,40E-05	4,92E-09	4,32E-05	930255
Main construction work							
Gypsum Plasterboard 12,5mm	m2	2,10E+00	1,80E-03	4,40E-03	1,40E-07	2,50E-04	4135,00
Isover Glass Wool 37, 80mm (Ceiling hanging)	m3	3,19E+01	8,86E-02	5,31E-02	3,38E-06	7,66E-02	371,20
Isover Glass Wool 37, 2x 45mm	m3	3,19E+01	8,86E-02	5,31E-02	3,38E-06	7,66E-02	372,15
Steel Studs (based on Danogips MR 45, 5m profiles per m2 wall, profile t=0,46mm, unfolded width 125mm, total m3 steel = 1,19, steel density 7850kg/m3), from LCC = 9,33ton steel	ton	2,59E+03	5,70E+00	4,90E-01	4,60E-05	1,10E+00	9,33
Smart vapour retarder (Icopal Hygrodiode) (Assumed 2 times normal vapour retarder)	m2	6,28E-01	2,40E-03	1,77E-04	9,12E-09	1,25E-04	4548,50
Vapour retarder tape	m	1,33E-01	4,64E-04	7,11E-05	3,00E-09	6,18E-05	20000,00
Anchors PVC, SPIT ISO S length 120mm, (Based on Ejot PVC anchors 120mm)	pcs	8,36E-02	2,69E-04	2,46E-05	4,48E-09	3,35E-05	10000,00
EPS insulation on existing floor, 40mm	m3	5,60E+01	1,20E-01	1,30E-02	1,60E-06	2,90E-01	374,20
EPS insulation around windows, 40mm	m3	5,60E+01	1,20E-01	1,30E-02	1,60E-06	2,90E-01	31,88
Wooden window reveals, thickness 20mm (based on painted pine wood)	m2	1,72E+00	8,43E-02	1,67E-02	1,34E-06	6,89E-03	1982,00
Window board from natural stone grey 30mm thick, density 2700kg/m3, 674m2 = 54,59ton	ton	1,77E+02	1,06E+00	3,20E-01	2,20E-05	3,70E-02	54,59

Interior vapour permeable paint (based on StoSil Colour), 0,14L/m2 = 579L	L	7,04E-01	5,31E-03	1,96E-03	1,37E-06	4,48E-04	579,00
Water repellent coating (Based on StoPrep Miral), 0,35kg/m2 wall = 1447kg	kg	7,56E-01	7,47E-03	9,58E-04	5,85E-07	2,68E-04	1447,00
Linoleum flooring (Based on ERFMI plain and decorative linoleum)	m2	2,60E+00	3,80E-02	1,20E-02	1,00E-08	2,30E-03	9355,00
Assumed building site electricity 50 kWh/day, 148 days (8x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	7400,00
Transport, material deliveries, assumed 100 km 20 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	2000,00
Transport, delivery/pickup of material containers, cabins, machinery, 100 km 7 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	700,00
Transport, delivery/empty/pickup of waste containers, 100 km 16 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1600,00
Transport, 4 cars, 50km each way (total 400km), for 148 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	59200,00
Electricity and heating (EL) for crew trailers for 148 days, with 106 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	15688,00
Renovation and replacement works							
Water repellent coating (Based on StoPrep Miral), 0,35kg/m2 wall = 1447kg (4 times in 50 years)	kg	7,56E-01	7,47E-03	9,58E-04	5,85E-07	2,68E-04	5788,00
Full replace of Gypsum Plasterboard 12,5mm	m2	2,10E+00	1,80E-03	4,40E-03	1,40E-07	2,50E-04	4135,00
Assumed building site electricity 19 kWh/day, 25 days (3x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	475,00
Transport, material deliveries, assumed 100 km 6 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	600,00
Transport, delivery/pickup of material containers, cabins, machinery, 100 km 12 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1200,00

Transport, delivery/empty/pickup of waste containers, 100 km 5 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	500,00
Transport, 2 cars, 50km each way (total 200km), for 180 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	36000,00
Electricity and heating (EL) for crew trailers for 180 days, with 53 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	9540,00

Roof (Usage phase not included) **Components**	Functional Unit	GWP	AP	EP	ODP	POCP	Quantity
Building Heating	kWh	4,00E-02	4,40E-04	8,40E-05	4,92E-09	4,32E-05	1136362
Main construction work							
Bitumen felt roofing (value are for 1 layer)	m2	3,55E+00	1,44E-02	2,00E-03	1,69E-07	3,14E-03	6694,00
Exterior EPS insulation on concrete deck 560mm	m3	5,60E+01	1,20E-01	1,30E-02	1,60E-06	2,90E-01	1685,60
Gypsum Plasterboard (ceiling hanging) 12,5mm	m2	2,10E+00	1,80E-03	4,40E-03	1,40E-07	2,50E-04	4840,18
Copper Cladding, cut length and fix into place, 0,7mm	kg	7,10E-01	7,90E-04	1,00E-04	1,30E-09	6,20E-05	36270,56
Wooden roof beams 100x225mm	m3	-6,07E+02	6,60E-06	8,99E-02	6,60E-06	2,65E-02	27,94
Wooden int. cross-battens 45x95mm	m3	-6,07E+02	6,60E-06	8,99E-02	6,60E-06	2,65E-02	8,24
Steel brackets for wood constructions (Bjælkesko 100x140mm) approximately 400g each	ton	2,62E+03	3,87E+01	1,24E+01	2,43E-04	2,13E+00	0,14
Steel brackets for wood constructions (Vinkelbeslag93x93x40mm) approximately 210g each	ton	2,62E+03	3,87E+01	1,24E+01	2,43E-04	2,13E+00	0,41
Wind tensioning straps (40x2mm) x600m	ton	2,62E+03	3,87E+01	1,24E+01	2,43E-04	2,13E+00	0,38
Wooden wall place (for roof beams) 100x200mm x2	m3	-6,07E+02	6,60E-06	8,99E-02	6,60E-06	2,65E-02	5,60
Anchors PVC, M24 length 290mm, (Based on Ejot PVC anchors 120mm x2,5)	pcs	2,09E-01	6,73E-04	6,15E-05	1,12E-08	8,38E-05	140,00
Mineral wool insulation class 37, 95mm	m3	4,41E+00	2,64E-02	3,24E-03	3,57E-07	1,62E-03	86,93
Mineral wool insulation 245mm x2	m3	4,41E+00	2,64E-02	3,24E-03	3,57E-07	1,62E-03	448,35

Vapour retarder (PE-foilie, Dafa ProFoil t=0,2mm)	m2	3,14E-01	1,20E-03	8,83E-05	4,56E-09	6,26E-05	3946,80
Smart vapour retarder (Icopal Hygrodiode) (Assumed 2 times normal vapour retarder)	m2	6,28E-01	2,40E-03	1,77E-04	9,12E-09	1,25E-04	370,70
Cement boards (Eternit) in air cavity, 13mm (values for 4mm, multiplied with 3)	m2	5,82E+01	1,16E-01	1,88E-02	8,55E-10	1,88E-02	578,00
Wood battens in the air cavity (wood spacing strips 25x50mm cc 800mm) x2	m3	-6,07E+02	6,60E-06	8,99E-02	6,60E-06	2,65E-02	1,77
Oriented strand board (OSB) 20mm (values 40mm, therefore divided by 2)	m2	-2,84E+02	4,86E-01	8,00E-02	-6,90E-07	9,85E-02	578,00
Exterior EPS insulation 70mm	m3	5,60E+01	1,20E-01	1,30E-02	1,60E-06	2,90E-01	40,46
Vapour retarder tape	m	1,33E-01	4,64E-04	7,11E-05	3,00E-09	6,18E-05	20000,00
Installing new roof gutters, half round in zinc, Ø250mm x140m and 5,05kg/m2	kg	3,30E+00	2,20E-02	2,50E-03	3,20E-07	1,40E-03	555,07
Assumed building site electricity 50 kWh/day, 135 days (8x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	6750,00
Transport, material deliveries, assumed 100 km 30 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	3000,00
Transport, delivery/pickup of material containers, cabins, machinery, 100 km 8 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	800,00
Transport, delivery/empty/pickup of waste containers, 100 km 20 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	2000,00
Transport, 4 cars, 50km each way (total 400km), for 135 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	54000,00
Electricity and heating (EL) for crew trailers for 135 days, with 106 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	14310,00
Renovation and replacement works							

Bitumen felt roofing 2 layers (value for 1 layer), fixing 50m2 9 times over 50 years (from LCC)	m2	3,55E+00	1,44E-02	2,00E-03	1,69E-07	3,14E-03	900,00
Bitumen felt roofing 2 layers (value for 1 layer), full replacement after 18 and 36 years (LCC)	m2	3,55E+00	1,44E-02	2,00E-03	1,69E-07	3,14E-03	13388,00
Gypsum Plasterboard (ceiling hanging) 12,5mm, full replacement after 35 years (LCC)	m2	2,10E+00	1,80E-03	4,40E-03	1,40E-07	2,50E-04	4840,18
Assumed building site electricity 19 kWh/day, 101 days (3x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	1919,00
Transport, material deliveries, assumed 100 km 10 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1000,00
Transport, delivery/pickup of material containers, cabins, machinery, 100 km 9 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	900,00
Transport, delivery/empty/pickup of waste containers, 100 km 10 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1000,00
Transport, 2 cars, 50km each way (total 200km), for 101 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	20200,00
Electricity and heating (EL) for crew trailers for 101 days, with 53 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	5353,00

Reference Building (Roof assemblies) Components	Functional Unit	GWP	AP	EP	ODP	POCP	Quantity
Building Heating	kWh	4,00E-02	4,40E-04	8,40E-05	4,92E-09	4,32E-05	1193310
Renovation and replacement works							
Bitumen felt roofing 2 layers (value for 1 layer), fixing 50m2 9 times over 50 years (from LCC)	m2	3,55E+00	1,44E-02	2,00E-03	1,69E-07	3,14E-03	900,00
Bitumen felt roofing 2 layers (value for 1 layer), full replacement after 18 and 36 years (LCC)	m2	3,55E+00	1,44E-02	2,00E-03	1,69E-07	3,14E-03	13388,00

Gypsum Plasterboard (ceiling hanging) 12,5mm, full replacement after 35 years (LCC)	m2	2,10E+00	1,80E-03	4,40E-03	1,40E-07	2,50E-04	4261,88
Assumed building site electricity 19 kWh/day, 97 days (3x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	1843,00
Transport, material deliveries, assumed 100 km 10 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1000,00
Transport, delivery/pickup of material containers, cabins, machinery, 100 km 9 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	900,00
Transport, delivery/empty/pickup of waste containers, 100 km 10 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1000,00
Transport, 2 cars, 50km each way (total 200km), for 97 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	19400,00
Electricity and heating (EL) for crew trailers for 97 days, with 53 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	5141,00

12.15 Appendix O

Input for the Life Cycle Assessment for the V-building

Reference Building (Wall assemblies) Components	Functional Unit	GWP	AP	EP	ODP	POCP	Quantity
Building Heating (annual quantity)	kWh	4,00E-02	4,40E-04	8,40E-05	4,92E-09	4,32E-05	1774116
Renovation and replacement works							
Replace interior cement based plaster 15mm (28,5kg/m2, 6815m2 = 194,23 ton), after 45 years	ton	1,28E+03	2,65E+00	2,80E-01	2,80E-07	1,90E-01	194,23
Assumed building site electricity 19 kWh/day, 164 days (3x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	3116,00
Transport, material deliveries, assumed 100 km 20 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	2000,00
Transport, delivery/pickup of material containers, cabins, machinery, 100 km 2 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	200,00
Transport, delivery/empty/pickup of waste containers, 100 km 20 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	2000,00
Transport, 2 cars, 50km each way (total 200km), for 164 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	32800,00
Electricity and heating (EL) for crew trailers for 164 days, with 53 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	8692,00

Wall ID = H Components	Functional Unit	GWP	AP	EP	ODP	POCP	Quantity
Building Heating (annual quantity)	kWh	4,00E-02	4,40E-04	8,40E-05	4,92E-09	4,32E-05	1266704
Main construction work							
Calcium Silicate Insulation boards 100mm (density 259 kg/m3, 6815m2 = 176,5ton)	ton	2,04E+03	2,15E+00	3,40E-01	4,56E-06	2,20E-01	176,50

Primer and Adhesive (based on Sto-Primer/Adhesive), 0,3kg/m2, 6815m2 = 1240,5 kg	kg	3,90E-01	2,31E-03	2,23E-03	8,00E-07	3,74E-04	2044,50
Interior vapour permeable paint (based on StoSil Colour), 0,14L/m2, 4135m2 = 579L	L	7,04E-01	5,31E-03	1,96E-03	1,37E-06	4,48E-04	954,10
Replace interior cement based plaster 15mm (28,5kg/m2, 6815m2 = 194,23 ton), after 45 years	ton	1,28E+03	2,65E+00	2,80E-01	2,80E-07	1,90E-01	194,23
No data for capillary active plaster found, instead the data for wet room plasterboards was used, as this board is suggested as an alternative to the capillary active plaster.	m2	3,48E+00	1,41E-02	8,70E-04	0,00E+00	1,50E-03	6815,00
Isover Glass Wool 37, 80mm (Ceiling hanging)	m3	3,19E+01	8,86E-02	5,31E-02	3,38E-06	7,66E-02	558,40
Anchors PVC, SPIT ISO S length 120mm, (Based on Ejot PVC anchors 120mm)	pcs	8,36E-02	2,69E-04	2,46E-05	4,48E-09	3,35E-05	17000,00
EPS insulation on existing floor, 40mm	m3	5,60E+01	1,20E-01	1,30E-02	1,60E-06	2,90E-01	530,60
EPS insulation around windows, 40mm	m3	5,60E+01	1,20E-01	1,30E-02	1,60E-06	2,90E-01	59,04
Wooden window reveals, thickness 20mm (based on painted pine wood)	m2	1,72E+00	8,43E-02	1,67E-02	1,34E-06	6,89E-03	3670,00
Window board from natural stone grey 30mm thick, density 2700kg/m3, 1250m2 = 54,59ton	ton	1,77E+02	1,06E+00	3,20E-01	2,20E-05	3,70E-02	101,25
Linoleum flooring (Based on ERFMI plain and decorative linoleum)	m2	2,60E+00	3,80E-02	1,20E-02	1,00E-08	2,30E-03	13265,00
Water repellent coating (Based on StoPrep Miral), 0,35kg/m2 wall = 2385kg	kg	7,56E-01	7,47E-03	9,58E-04	5,85E-07	2,68E-04	2385,00
Assumed building site electricity 50 kWh/day, 250 days (8x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	12500,00
Transport, material deliveries, assumed 100 km 30 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	3000,00
Transport, delivery/pickup of material containers, cabins, machinery, 100 km 7 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	700,00

Transport, delivery/empty/pickup of waste containers, 100 km 23 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	2300,00
Transport, 4 cars, 50km each way (total 400km), for 250 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	100000,00
Electricity and heating (EL) for crew trailers for 250 days, with 106 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	26500,00
Renovation and replacement works							
Water repellent coating (Based on StoPrep Miral), 0,35kg/m2 wall = 2385kg (4 times in 50 years)	kg	7,56E-01	7,47E-03	9,58E-04	5,85E-07	2,68E-04	9540,00
Full replacement of wet room plasterboard every 45 years acc. to LCC	m2	3,48E+00	1,41E-02	8,70E-04	0,00E+00	1,50E-03	4135,00
Assumed building site electricity 19 kWh/day, 164 days (3x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	3116,00
Transport, material deliveries, assumed 100 km 8 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	800,00
Transport, delivery/pickup of material containers, cabins, machinery, 100 km 12 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1200,00
Transport, delivery/empty/pickup of waste containers, 100 km 6 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	600,00
Transport, 2 cars, 50km each way (total 200km), for 419 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	83800,00
Electricity and heating (EL) for crew trailers for 419 days, with 53 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	22207,00

Wall ID = N **Components**	Functional Unit	GWP	AP	EP	ODP	POCP	Quantity
Building Heating (annual quantity)	kWh	4,00E-02	4,40E-04	8,40E-05	4,92E-09	4,32E-05	1265770

Main construction work							
Gypsum Plasterboard 12,5mm	m2	2,10E+00	1,80E-03	4,40E-03	1,40E-07	2,50E-04	6815,00
Smart vapour retarder (Icopal Hygrodiode) (Assumed 2 times normal vapour retarder)	m2	6,28E-01	2,40E-03	1,77E-04	9,12E-09	1,25E-04	7496,50
Vapour retarder tape	m	1,33E-01	4,64E-04	7,11E-05	3,00E-09	6,18E-05	30000,00
Aspen Aerogel Spaceloft Insulation 30mm (values for 10mm, area multiplied by 3)	m2	1,27E+01	5,99E-02	6,36E-03	3,63E-06	4,37E-03	20445,00
Interior vapour permeable paint (based on StoSil Colour), 0,14L/m2 = 954,1L	L	7,04E-01	5,31E-03	1,96E-03	1,37E-06	4,48E-04	954,10
New interior cement based plater 10mm (19kg/m2, 6815m2 = 129,5ton)	ton	1,28E+03	2,65E+00	2,80E-01	2,80E-07	1,90E-01	129,50
Wood battens 25x25mm (assumed 2m per m2 wall, 6815m2 = 8,52m3)	m3	-6,07E+02	6,60E-06	8,99E-02	6,60E-06	2,65E-02	8,52
Isover Glass Wool 37, 80mm (Ceiling hanging)	m3	3,19E+01	8,86E-02	5,31E-02	3,38E-06	7,66E-02	558,40
Anchors PVC, SPIT ISO S length 120mm, (Based on Ejot PVC anchors 120mm)	pcs	8,36E-02	2,69E-04	2,46E-05	4,48E-09	3,35E-05	17000,00
EPS insulation on existing floor, 40mm	m3	5,60E+01	1,20E-01	1,30E-02	1,60E-06	2,90E-01	530,60
EPS insulation around windows, 40mm	m3	5,60E+01	1,20E-01	1,30E-02	1,60E-06	2,90E-01	59,04
Wooden window reveals, thickness 20mm (based on painted pine wood)	m2	1,72E+00	8,43E-02	1,67E-02	1,34E-06	6,89E-03	3670,00
Window board from natural stone grey 30mm thick, density 2700kg/m3, 1250m2 = 54,59ton	ton	1,77E+02	1,06E+00	3,20E-01	2,20E-05	3,70E-02	101,25
Linoleum flooring (Based on ERFMI plain and decorative linoleum)	m2	2,60E+00	3,80E-02	1,20E-02	1,00E-08	2,30E-03	13265,00
Water repellent coating (Based on StoPrep Miral), 0,35kg/m2 wall = 2385kg	kg	7,56E-01	7,47E-03	9,58E-04	5,85E-07	2,68E-04	2385,00
Assumed building site electricity 50 kWh/day, 272 days (8x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	13600,00

Transport, material deliveries, assumed 100 km 30 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	3000,00
Transport, delivery/pickup of material containers, cabins, machinery, 100 km 7 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	700,00
Transport, delivery/empty/pickup of waste containers, 100 km 23 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	2300,00
Transport, 4 cars, 50km each way (total 400km), for 272 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	108800,00
Electricity and heating (EL) for crew trailers for 272 days, with 106 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	28832,00
Renovation and replacement works							
Water repellent coating (Based on StoPrep Miral), 0,35kg/m2 wall = 2385kg (4 times in 50 years)	kg	7,56E-01	7,47E-03	9,58E-04	5,85E-07	2,68E-04	9540,00
Full replace of Gypsum Plasterboard 12,5mm	m2	2,10E+00	1,80E-03	4,40E-03	1,40E-07	2,50E-04	6815,00
Assumed building site electricity 19 kWh/day, 41 days (3x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	779,00
Transport, material deliveries, assumed 100 km 8 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	800,00
Transport, delivery/pickup of material containers, cabins, machinery, 100 km 12 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1200,00
Transport, delivery/empty/pickup of waste containers, 100 km 6 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	600,00
Transport, 2 cars, 50km each way (total 200km), for 296 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	59200,00
Electricity and heating (EL) for crew trailers for 296 days, with 53 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	15688,00

Wall ID = O **Components**	Functional Unit	GWP	AP	EP	ODP	POCP	Quantity
Building Heating (annual quantity)	kWh	4,00E-02	4,40E-04	8,40E-05	4,92E-09	4,32E-05	1280180
Main construction work							
Gypsum Plasterboard 12,5mm	m2	2,10E+00	1,80E-03	4,40E-03	1,40E-07	2,50E-04	6815,00
Isover Glass Wool 37, 80mm (Ceiling hanging)	m3	3,19E+01	8,86E-02	5,31E-02	3,38E-06	7,66E-02	558,40
Isover Glass Wool 37, 2x 45mm	m3	3,19E+01	8,86E-02	5,31E-02	3,38E-06	7,66E-02	613,35
Steel Studs (based on Danogips MR 45, 5m profiles per m2 wall, profile t=0,46mm, unfolded width 125mm, total m3 steel = 1,96, steel density 7850kg/m3), from LCC = 15.38 ton steel	ton	2,59E+03	5,70E+00	4,90E-01	4,60E-05	1,10E+00	15,38
Smart vapour retarder (Icopal Hygrodiode) (Assumed 2 times normal vapour retarder)	m2	6,28E-01	2,40E-03	1,77E-04	9,12E-09	1,25E-04	7496,50
Vapour retarder tape	m	1,33E-01	4,64E-04	7,11E-05	3,00E-09	6,18E-05	30000,00
Anchors PVC, SPIT ISO S length 120mm, (Based on Ejot PVC anchors 120mm)	pcs	8,36E-02	2,69E-04	2,46E-05	4,48E-09	3,35E-05	17000,00
EPS insulation on existing floor, 40mm	m3	5,60E+01	1,20E-01	1,30E-02	1,60E-06	2,90E-01	530,60
EPS insulation around windows, 40mm	m3	5,60E+01	1,20E-01	1,30E-02	1,60E-06	2,90E-01	59,04
Wooden window reveals, thickness 20mm (based on painted pine wood)	m2	1,72E+00	8,43E-02	1,67E-02	1,34E-06	6,89E-03	3670,00
Window board from natural stone grey 30mm thick, density 2700kg/m3, 1250m2 = 54,59ton	ton	1,77E+02	1,06E+00	3,20E-01	2,20E-05	3,70E-02	101,25
Interior vapour permeable paint (based on StoSil Colour), 0,14L/m2 = 954,1L	L	7,04E-01	5,31E-03	1,96E-03	1,37E-06	4,48E-04	954,10
Water repellent coating (Based on StoPrep Miral), 0,35kg/m2 wall = 2385kg	kg	7,56E-01	7,47E-03	9,58E-04	5,85E-07	2,68E-04	2385,00
Linoleum flooring (Based on ERFMI plain and decorative linoleum)	m2	2,60E+00	3,80E-02	1,20E-02	1,00E-08	2,30E-03	13265,00

Assumed building site electricity 50 kWh/day, 237 days (8x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	11850,00
Transport, material deliveries, assumed 100 km 30 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	3000,00
Transport, delivery/pickup of material containers, cabins, machinery, 100 km 7 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	700,00
Transport, delivery/empty/pickup of waste containers, 100 km 23 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	2300,00
Transport, 4 cars, 50km each way (total 400km), for 237 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	94800,00
Electricity and heating (EL) for crew trailers for 237 days, with 106 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	25122,00
Renovation and replacement works							
Water repellent coating (Based on StoPrep Miral), 0,35kg/m2 wall = 2385kg (4 times in 50 years)	kg	7,56E-01	7,47E-03	9,58E-04	5,85E-07	2,68E-04	9540,00
Full replace of Gypsum Plasterboard 12,5mm	m2	2,10E+00	1,80E-03	4,40E-03	1,40E-07	2,50E-04	6815,00
Assumed building site electricity 19 kWh/day, 41 days (3x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	779,00
Transport, material deliveries, assumed 100 km 8 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	800,00
Transport, delivery/pickup of material containers, cabins, machinery, 100 km 12 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1200,00
Transport, delivery/empty/pickup of waste containers, 100 km 6 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	600,00
Transport, 2 cars, 50km each way (total 200km), for 296 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	59200,00

Electricity and heating (EL) for crew trailers for 296 days, with 53 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	15688,00

Roof (Usage phase not included) **Components**	Functional Unit	GWP	AP	EP	ODP	POCP	Quantity
Building Heating (annual quantity)	kWh	4,00E-02	4,40E-04	8,40E-05	4,92E-09	4,32E-05	1710538
Main construction work							
Bitumen felt roofing (value are for 1 layer)	m2	3,55E+00	1,44E-02	2,00E-03	1,69E-07	3,14E-03	12250,00
Exterior EPS insulation on concrete deck 560mm	m3	5,60E+01	1,20E-01	1,30E-02	1,60E-06	2,90E-01	3347,46
Gypsum Plasterboard (ceiling hanging) 12,5mm	m2	2,10E+00	1,80E-03	4,40E-03	1,40E-07	2,50E-04	7693,40
Copper Cladding, cut length and fix into place, 0,7mm	kg	7,10E-01	7,90E-04	1,00E-04	1,30E-09	6,20E-05	44531,20
Wooden roof beams 100x225mm	m3	-6,07E+02	6,60E-06	8,99E-02	6,60E-06	2,65E-02	25,24
Wooden int. cross-battens 45x95mm	m3	-6,07E+02	6,60E-06	8,99E-02	6,60E-06	2,65E-02	7,31
Steel brackets for wood constructions (Bjælkesko 100x140mm) approximately 400g each	ton	2,62E+03	3,87E+01	1,24E+01	2,43E-04	2,13E+00	0,12
Steel brackets for wood constructions (Vinkelbeslag93x93x40mm) approximately 210g each	ton	2,62E+03	3,87E+01	1,24E+01	2,43E-04	2,13E+00	0,37
Wind tensioning straps (40x2mm) x600m	ton	2,62E+03	3,87E+01	1,24E+01	2,43E-04	2,13E+00	0,33
Wooden wall place (for roof beams) 100x200mm x2	m3	-6,07E+02	6,60E-06	8,99E-02	6,60E-06	2,65E-02	4,85
Anchors PVC, M24 length 290mm, (Based on Ejot PVC anchors 120mm x2,5)	pcs	2,09E-01	6,73E-04	6,15E-05	1,12E-08	8,38E-05	120,00
Mineral wool insulation class 37, 95mm	m3	4,41E+00	2,64E-02	3,24E-03	3,57E-07	1,62E-03	81,42
Mineral wool insulation 245mm x2	m3	4,41E+00	2,64E-02	3,24E-03	3,57E-07	1,62E-03	419,93
Vapour retarder (PE-foilie, Dafa ProFoil t=0,2mm)	m2	3,14E-01	1,20E-03	8,83E-05	4,56E-09	6,26E-05	7356,36

Smart vapour retarder (Icopal Hygrodiode) (Assumed 2 times normal vapour retarder)	m2	6,28E-01	2,40E-03	1,77E-04	9,12E-09	1,25E-04	162,14
Cement boards (Eternit) in air cavity, 13mm (values for 4mm, multiplied with 3)	m2	5,82E+01	1,16E-01	1,88E-02	8,55E-10	1,88E-02	710,00
Wood battens in the air cavity (wood spacing strips 25x50mm cc 800mm) x2	m3	-6,07E+02	6,60E-06	8,99E-02	6,60E-06	2,65E-02	2,08
Oriented strand board (OSB) 20mm (values 40mm, therefore divided by 2)	m2	-2,84E+02	4,86E-01	8,00E-02	-6,90E-07	9,85E-02	710,00
Exterior EPS insulation 70mm	m3	5,60E+01	1,20E-01	1,30E-02	1,60E-06	2,90E-01	49,70
Vapour retarder tape	m	1,33E-01	4,64E-04	7,11E-05	3,00E-09	6,18E-05	30000,00
Installing new roof gutters, half round in zinc, Ø250mm x121m and 5,05kg/m2	kg	3,30E+00	2,20E-02	2,50E-03	3,20E-07	1,40E-03	480,55
Assumed building site electricity 50 kWh/day, 196 days (8x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	9800,00
Transport, material deliveries, assumed 100 km 30 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	3000,00
Transport, delivery/pickup of material containers, cabins, machinery, 100 km 8 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	800,00
Transport, delivery/empty/pickup of waste containers, 100 km 26 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	2600,00
Transport, 4 cars, 50km each way (total 400km), for 196 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	78400,00
Electricity and heating (EL) for crew trailers for 196 days, with 106 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	20776,00
Renovation and replacement works							
Bitumen felt roofing 2 layers (value for 1 layer), fixing 50m2 9 times over 50 years (from LCC)	m2	3,55E+00	1,44E-02	2,00E-03	1,69E-07	3,14E-03	1800,00

Bitumen felt roofing 2 layers (value for 1 layer), full replacement after 18 and 36 years (LCC)	m2	3,55E+00	1,44E-02	2,00E-03	1,69E-07	3,14E-03	24500,00
Gypsum Plasterboard (ceiling hanging) 12,5mm, full replacement after 35 years (LCC)	m2	2,10E+00	1,80E-03	4,40E-03	1,40E-07	2,50E-04	7693,44
Assumed building site electricity 19 kWh/day, 178 days (3x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	3382,00
Transport, material deliveries, assumed 100 km 13 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1300,00
Transport, delivery/pickup of material containers, cabins, machinery, 100 km 9 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	900,00
Transport, delivery/empty/pickup of waste containers, 100 km 13 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1300,00
Transport, 2 cars, 50km each way (total 200km), for 178 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	35600,00
Electricity and heating (EL) for crew trailers for 178 days, with 53 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	9434,00

Reference Building (Roof assemblies) Components	Functional Unit	GWP	AP	EP	ODP	POCP	Quantity
Building Heating (annual quantity)	kWh	4,00E-02	4,40E-04	8,40E-05	4,92E-09	4,32E-05	1774116
Renovation and replacement works							
Bitumen felt roofing 2 layers (value for 1 layer), fixing 100m2 9 times over 50 years (from LCC)	m2	3,55E+00	1,44E-02	2,00E-03	1,69E-07	3,14E-03	1800,00
Bitumen felt roofing 2 layers (value for 1 layer), full replacement after 18 and 36 years (LCC)	m2	3,55E+00	1,44E-02	2,00E-03	1,69E-07	3,14E-03	24500,00
Gypsum Plasterboard (ceiling hanging) 12,5mm, full replacement after 35 years (LCC)	m2	2,10E+00	1,80E-03	4,40E-03	1,40E-07	2,50E-04	6982,40

Assumed building site electricity 19 kWh/day, 173 days (3x800W power tools used 8 h/d)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	3287,00
Transport, material deliveries, assumed 100 km 13 times (based on material quantities LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1300,00
Transport, delivery/pickup of material containers, cabins, machinery, 100 km 9 times (LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	900,00
Transport, delivery/empty/pickup of waste containers, 100 km 13 times (from LCC)	km	6,59E-01	3,11E-03	7,20E-04	1,33E-09	2,24E-04	1300,00
Transport, 2 cars, 50km each way (total 200km), for 173 days (from LCC)	km	1,37E-01	6,24E-04	1,44E-04	2,75E-10	4,55E-05	34600,00
Electricity and heating (EL) for crew trailers for 173 days, with 53 kWh/day (from LCC)	kWh	6,23E+00	6,79E-03	6,58E-04	8,33E-09	3,81E-04	9169,00

12.16 Appendix P

Results from the future climate energy simulations for the A-building

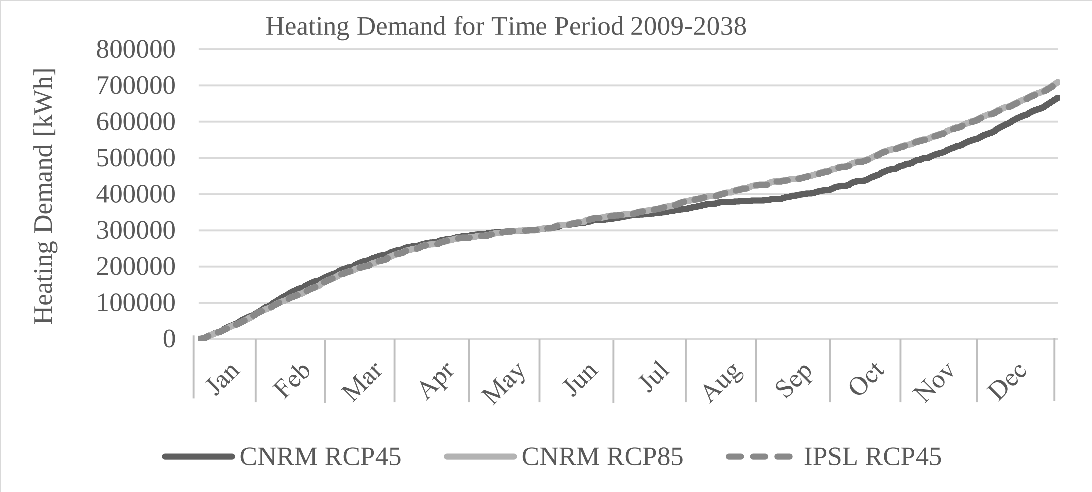

Figure 201: Annual heating demand for the wall case N in the A-building during the time period 2009-2038, for the city of Lund.

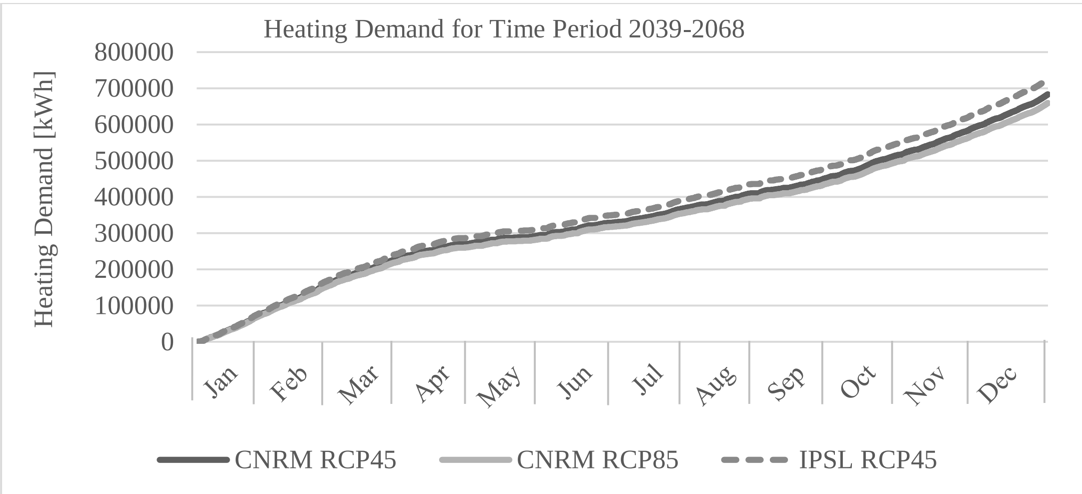

Figure 202: Annual heating demand for the wall case N in the A-building during the time period 2039-2068, for the city of Lund.

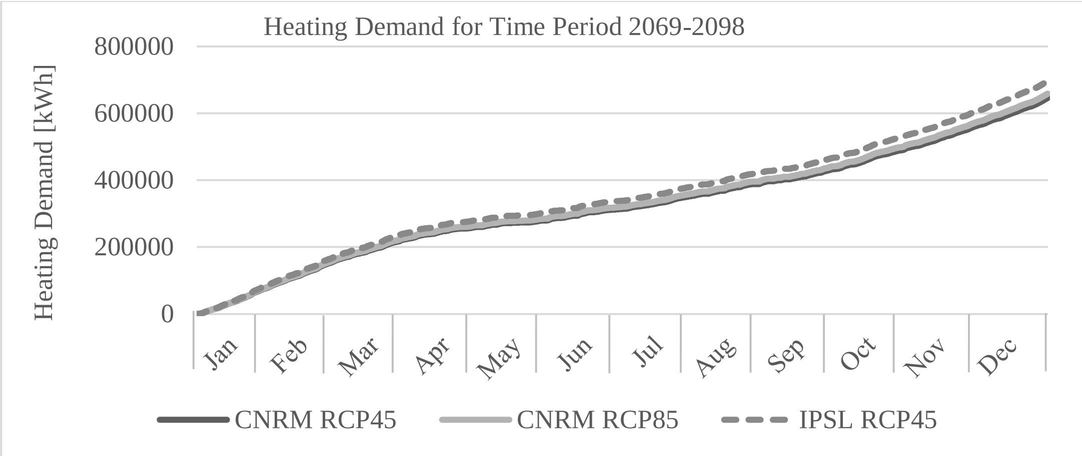

Figure 203: Annual heating demand for the wall case N in the A-building during the time period 2069-2098, for the city of Lund.

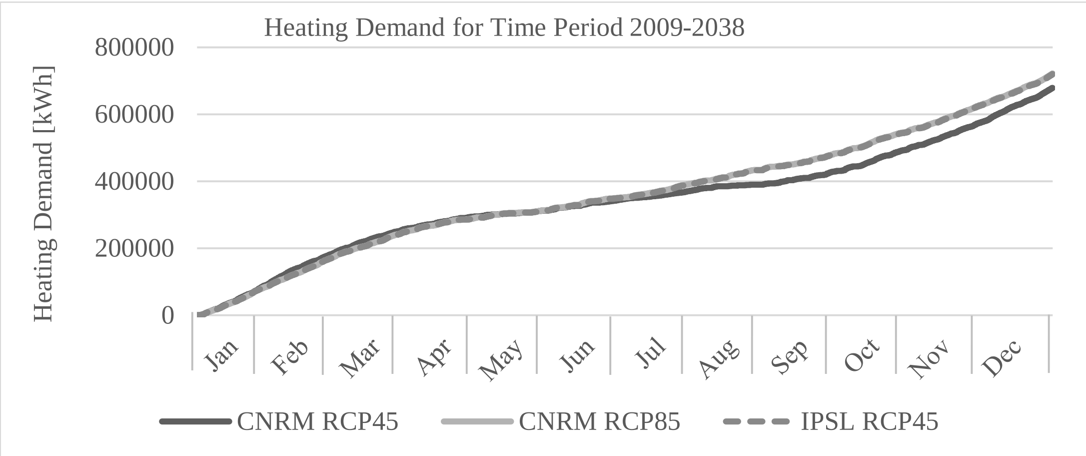

Figure 204: Annual heating demand for the wall case O in the A-building during the time period 2009-2038, for the city of Lund.

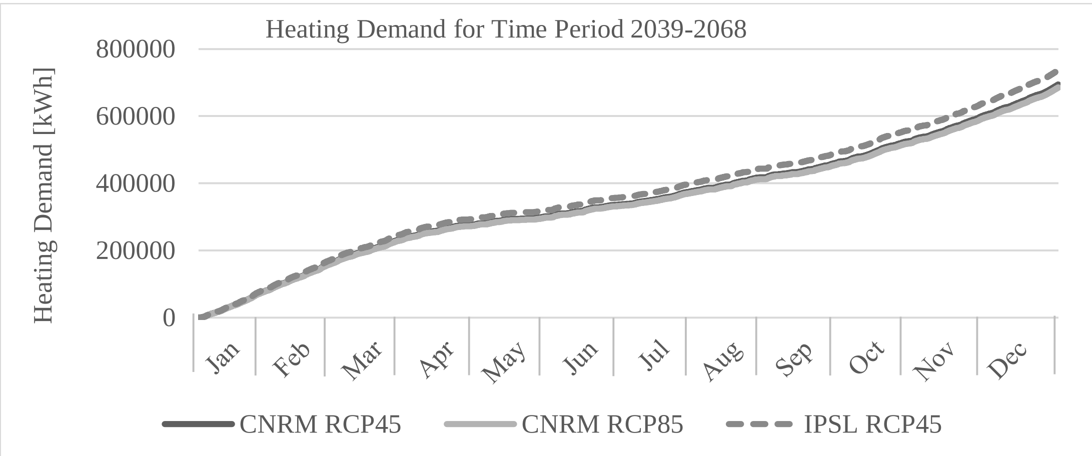

Figure 205: Annual heating demand for the wall case O in the A-building during the time period 2039-2068, for the city of Lund.

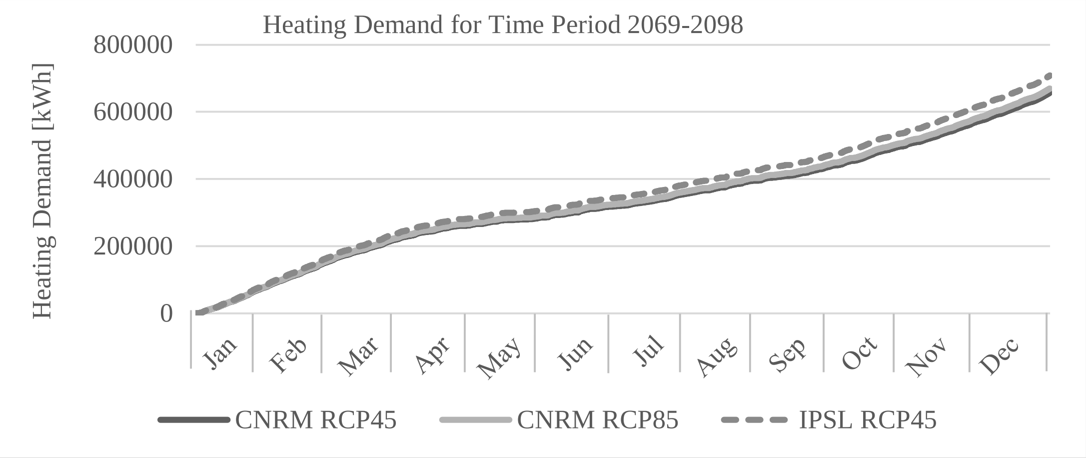

Figure 206: Annual heating demand for the wall case O in the A-building during the time period 2069-2098, for the city of Lund.

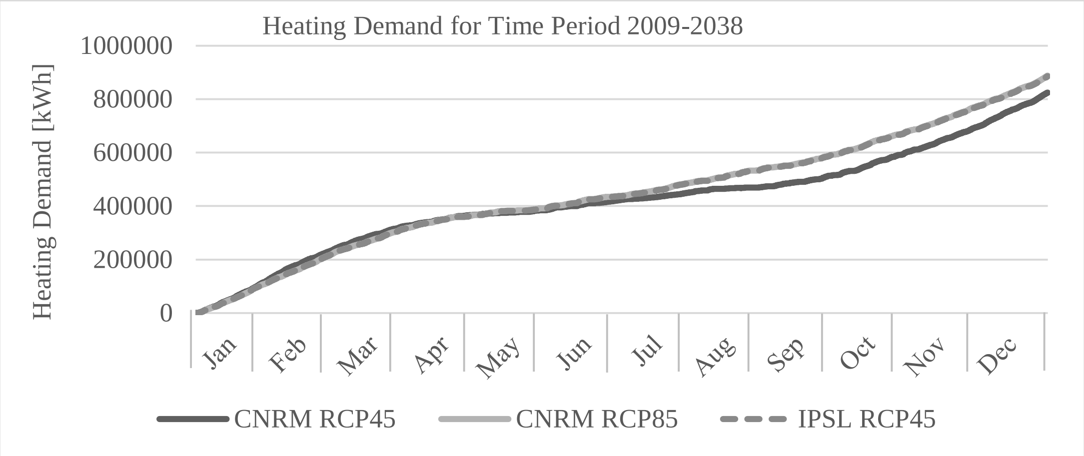

Figure 207: Annual heating demand for the roof case in the A-building during the time period 2009-2038, for the city of Lund.

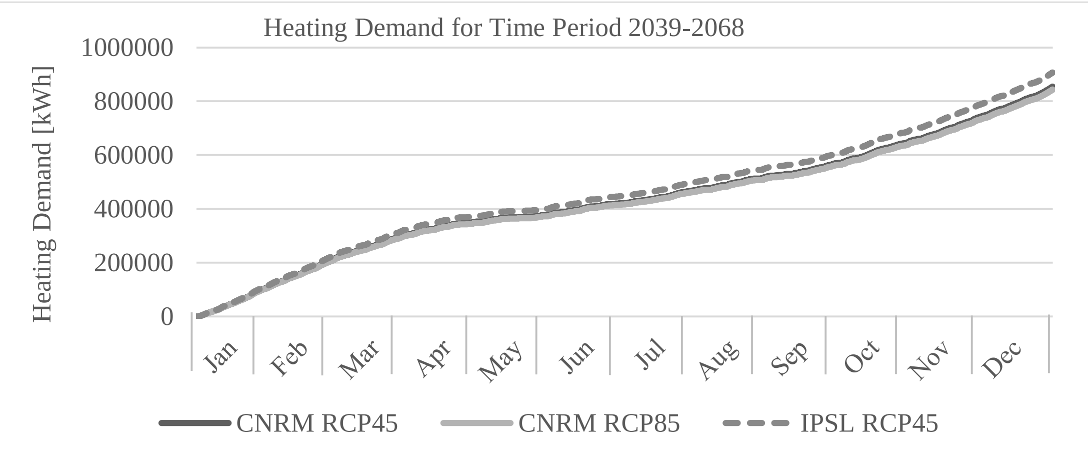

Figure 208: Annual heating demand for the roof case in the A-building during the time period 2039-2068, for the city of Lund.

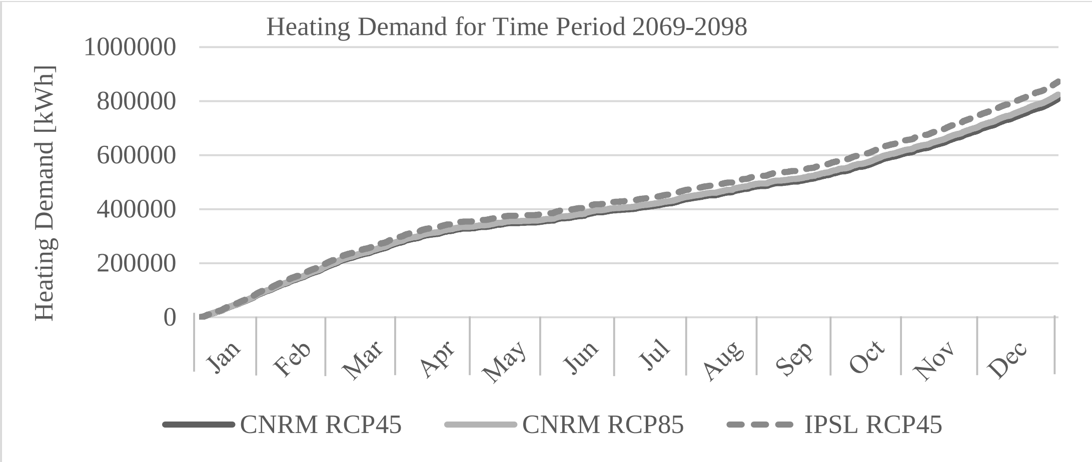

Figure 209: Annual heating demand for the roof case in the A-building during the time period 2069-2098, for the city of Lund.

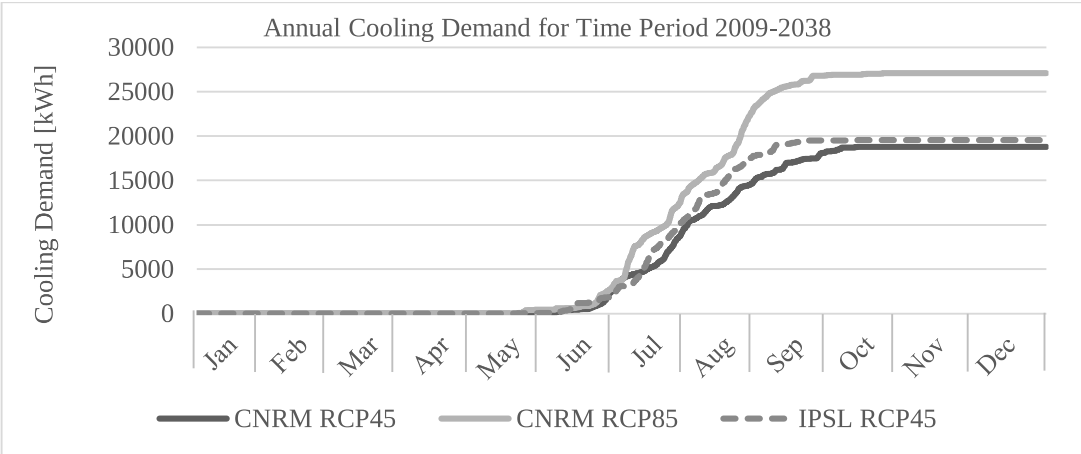

Figure 210: Annual cooling demand for the wall case H in the A-building during the time period 2009-2038, for the city of Lund.

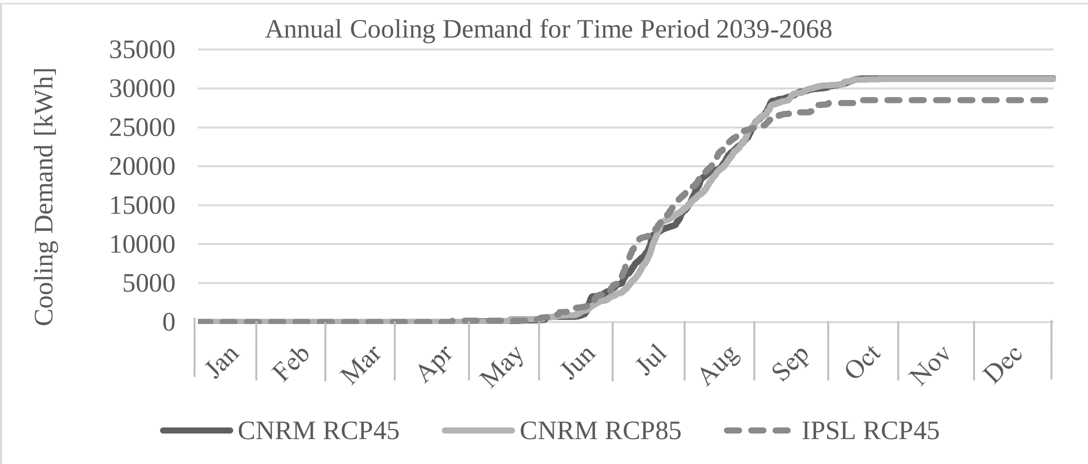

Figure 211: Annual cooling demand for the wall case H in the A-building during the time period 2039-2068, for the city of Lund.

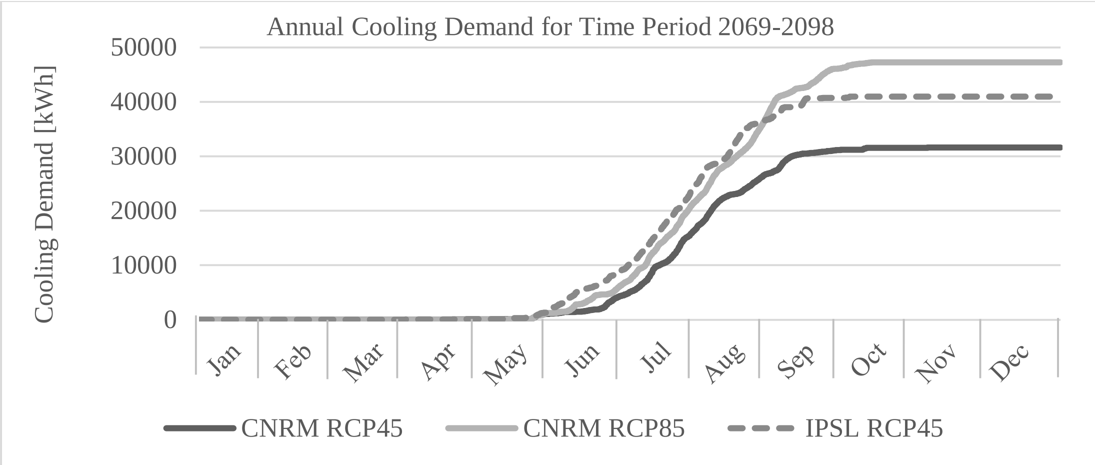

Figure 212: Annual cooling demand for the wall case H in the A-building during the time period 2069-2098, for the city of Lund.

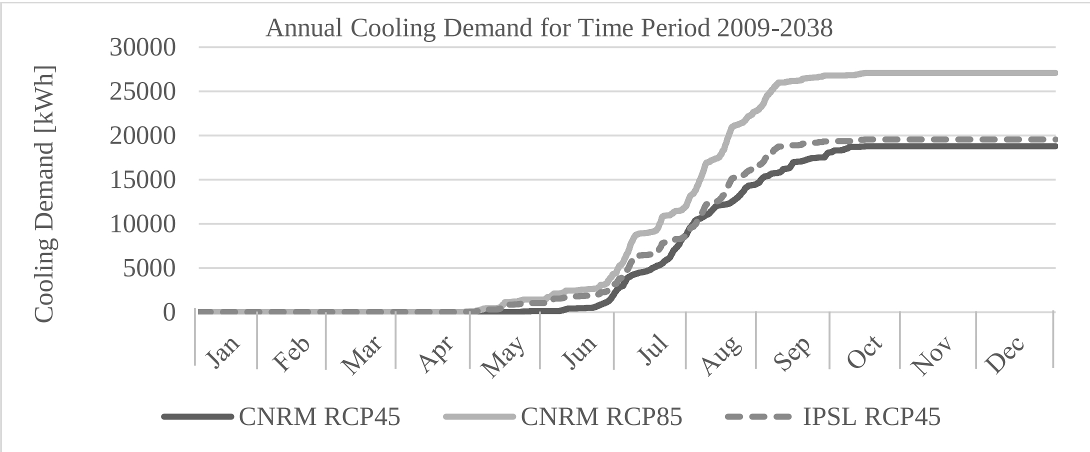

Figure 213: Annual cooling demand for the wall case N in the A-building during the time period 2009-2038, for the city of Lund.

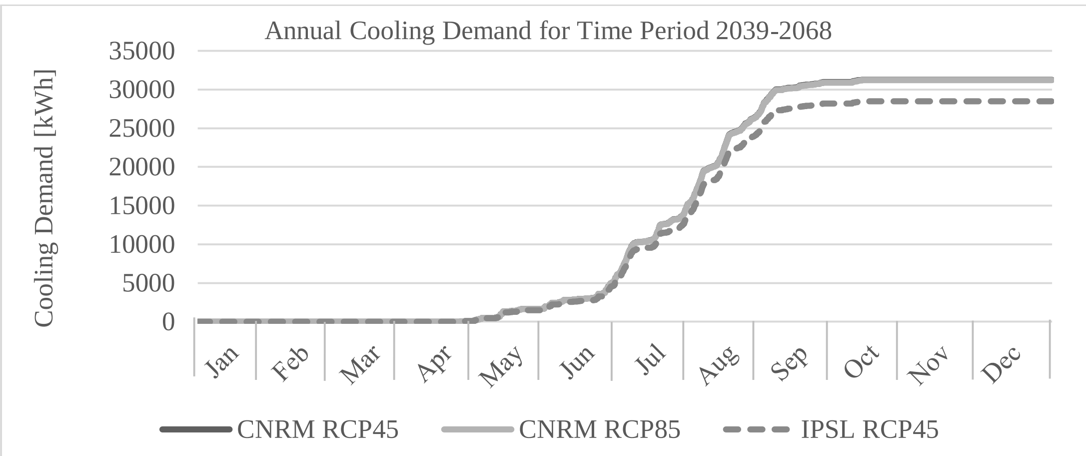

Figure 214: Annual cooling demand for the wall case N in the A-building during the time period 2039-2068, for the city of Lund.

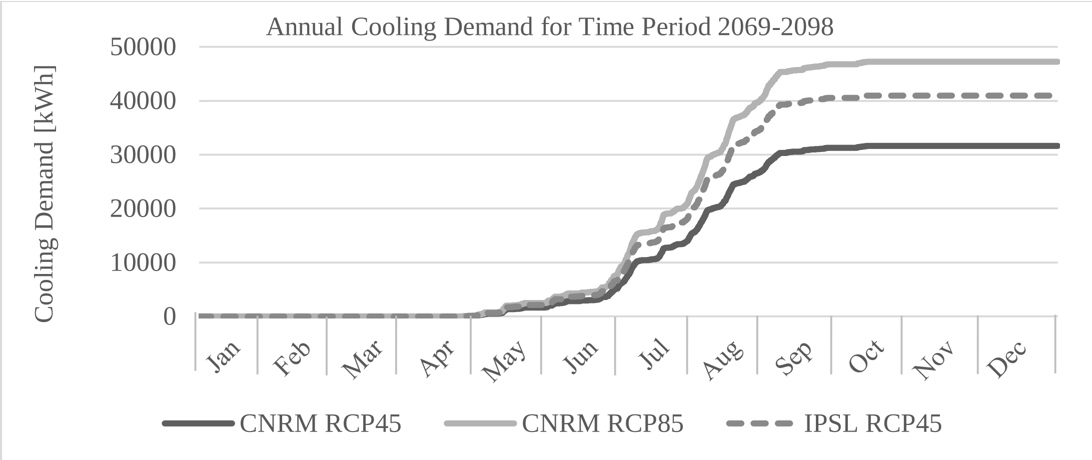

Figure 215: Annual cooling demand for the wall case N in the A-building during the time period 2069-2098, for the city of Lund.

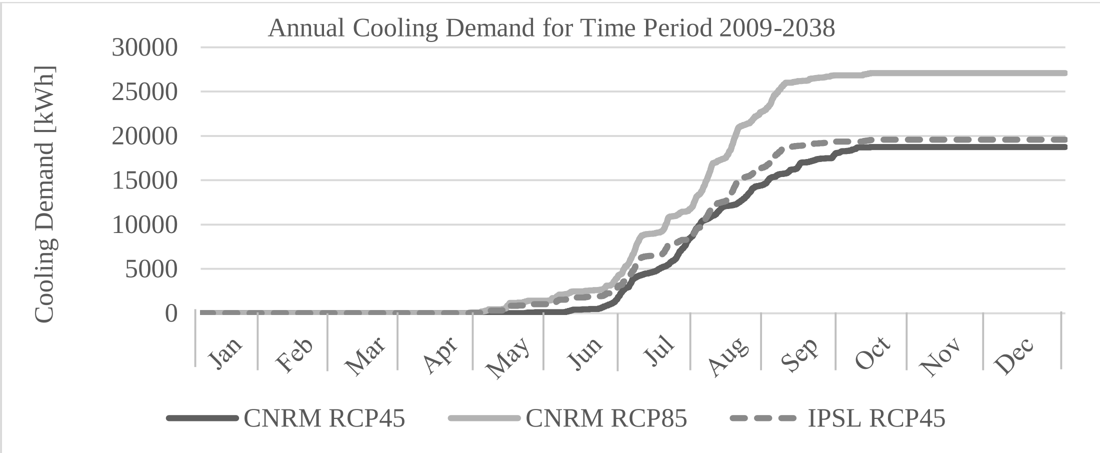

Figure 216: Annual cooling demand for the wall case O in the A-building during the time period 2009-2038, for the city of Lund.

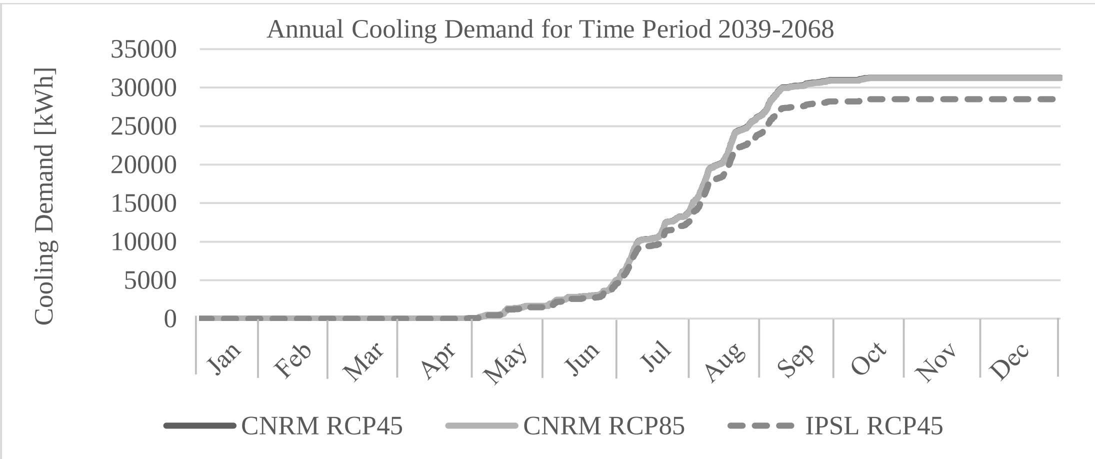

Figure 217: Annual cooling demand for the wall case O in the A-building during the time period 2039-2068, for the city of Lund.

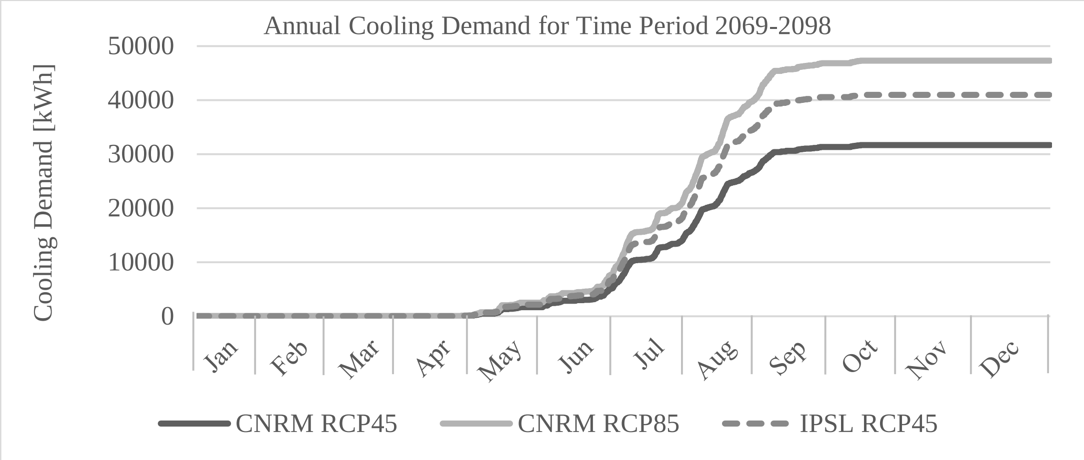

Figure 218: Annual cooling demand for the wall case O in the A-building during the time period 2069-2098, for the city of Lund.

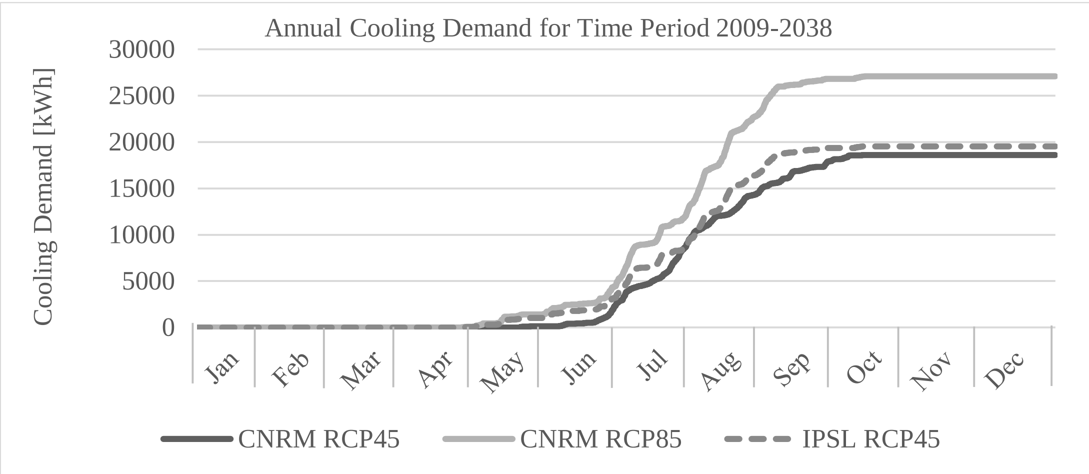

Figure 219: Annual cooling demand for the roof case in the A-building during the time period 2009-2038, for the city of Lund.

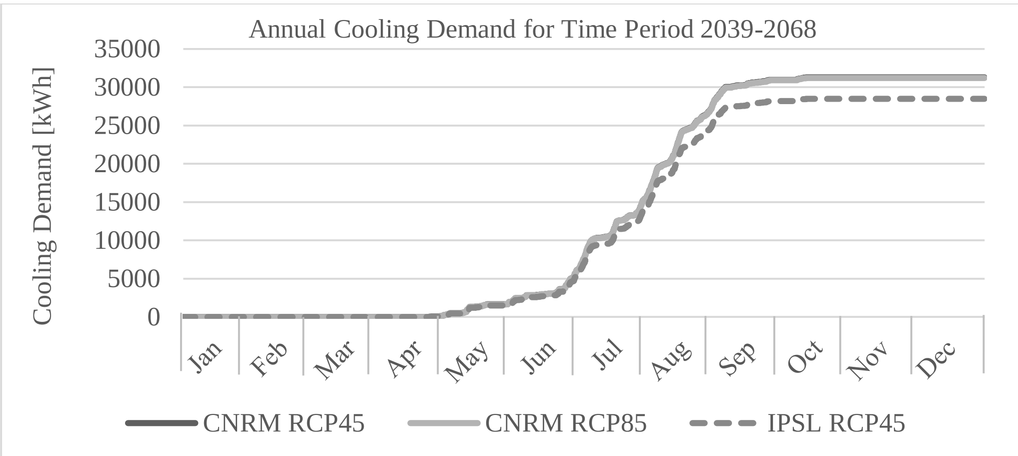

Figure 220: Annual cooling demand for the roof case in the A-building during the time period 2039-2068, for the city of Lund.

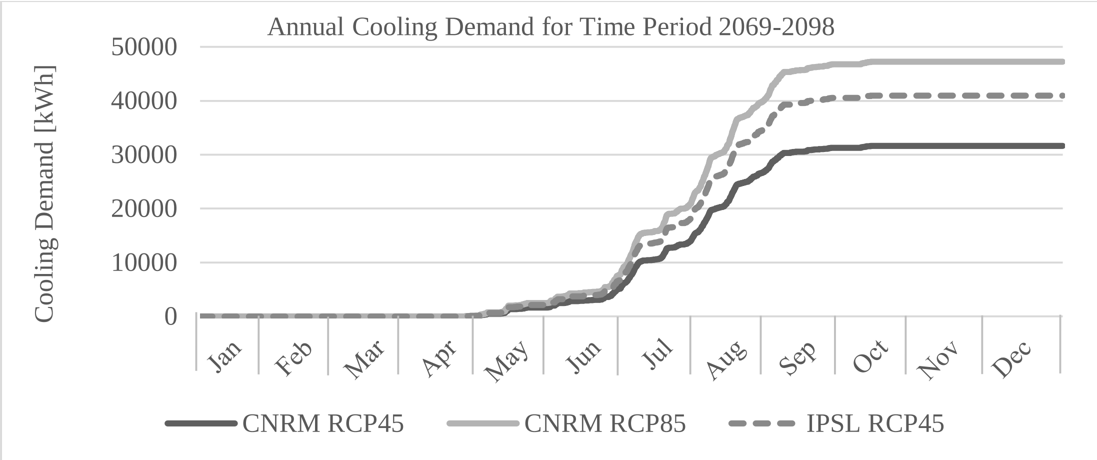

Figure 221: Annual cooling demand for the roof case in the A-building during the time period 2069-2098, for the city of Lund.

12.17 Appendix Q

Results from the future climate energy simulations for the V-building

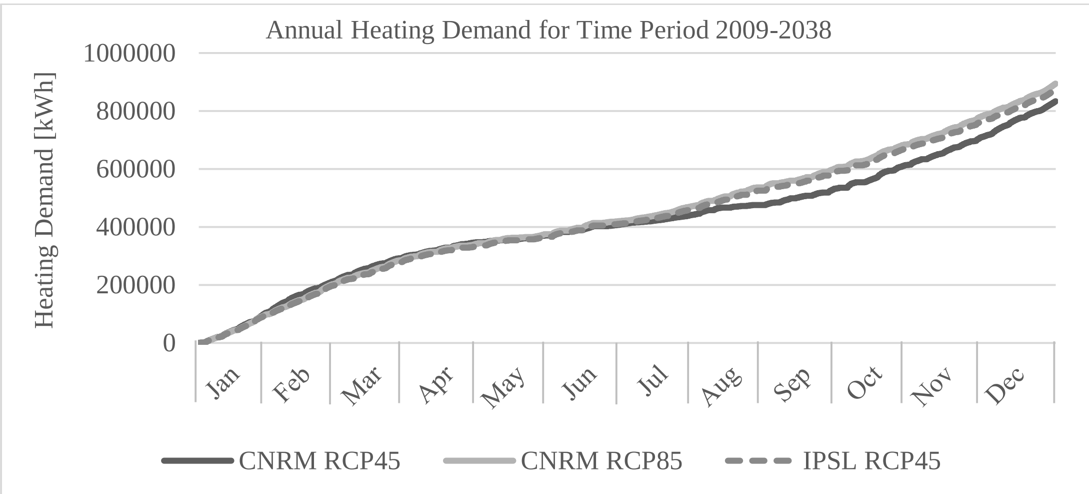

Figure 222: Annual heating demand for the wall case N in the V-building during the time period 2009-2038, for the city of Lund.

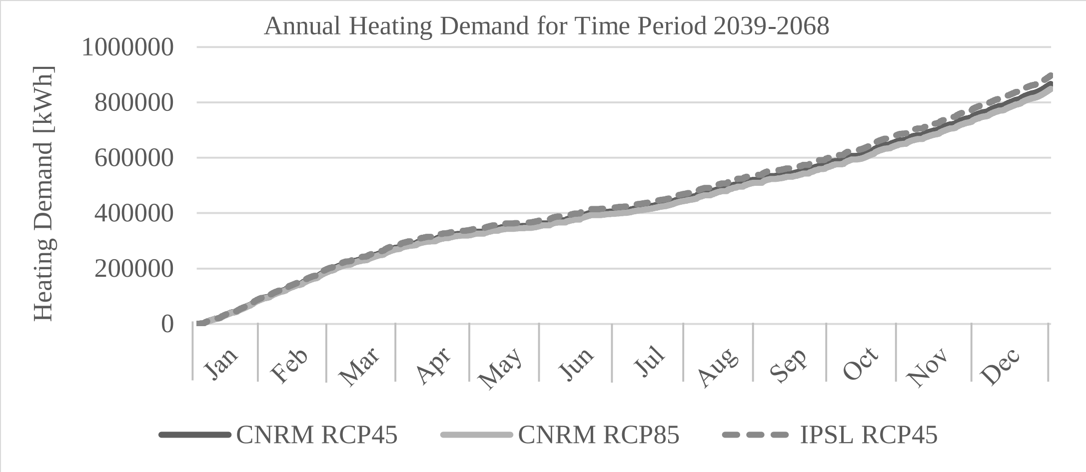

Figure 223: Annual heating demand for the wall case N in the V-building during the time period 2039-2068, for the city of Lund.

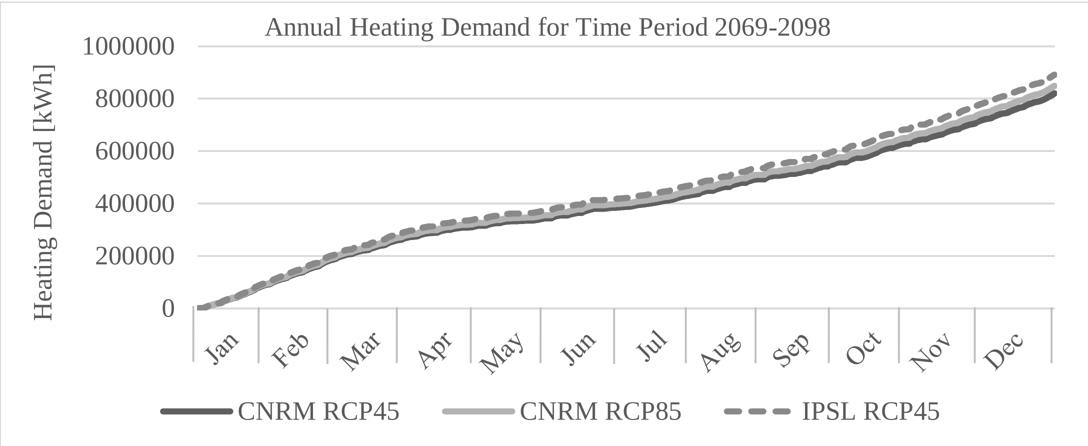

Figure 224: Annual heating demand for the wall case N in the V-building during the time period 2069-2098, for the city of Lund.

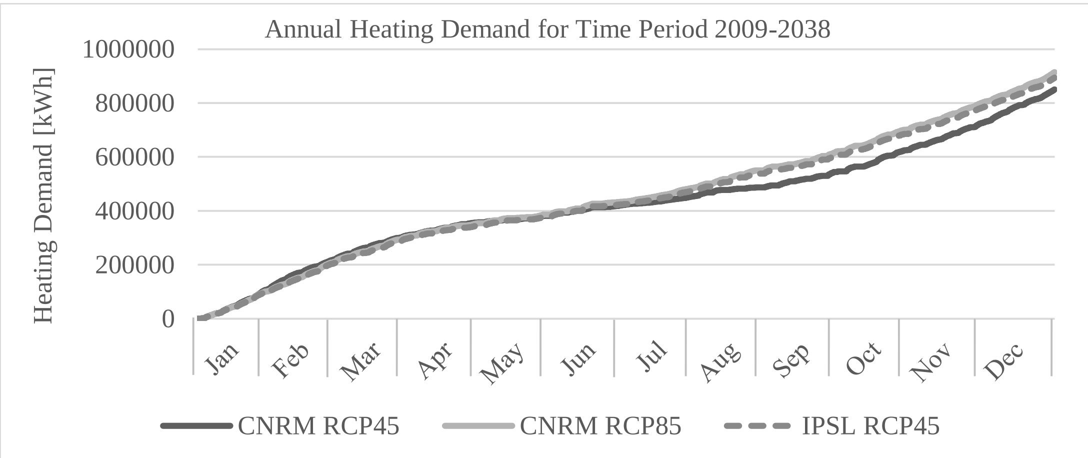

Figure 225: Annual heating demand for the wall case O in the V-building during the time period 2009-2038, for the city of Lund.

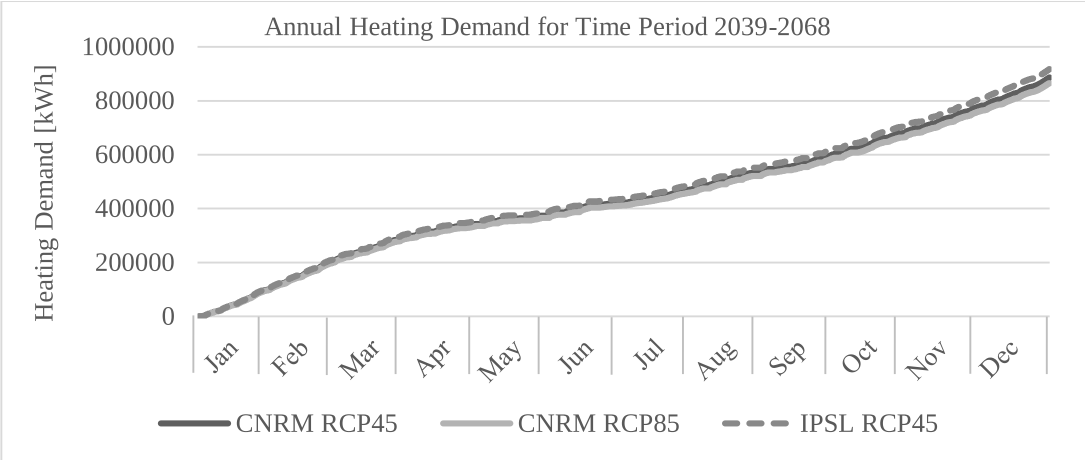

Figure 226: Annual heating demand for the wall case O in the V-building during the time period 2039-2068, for the city of Lund.

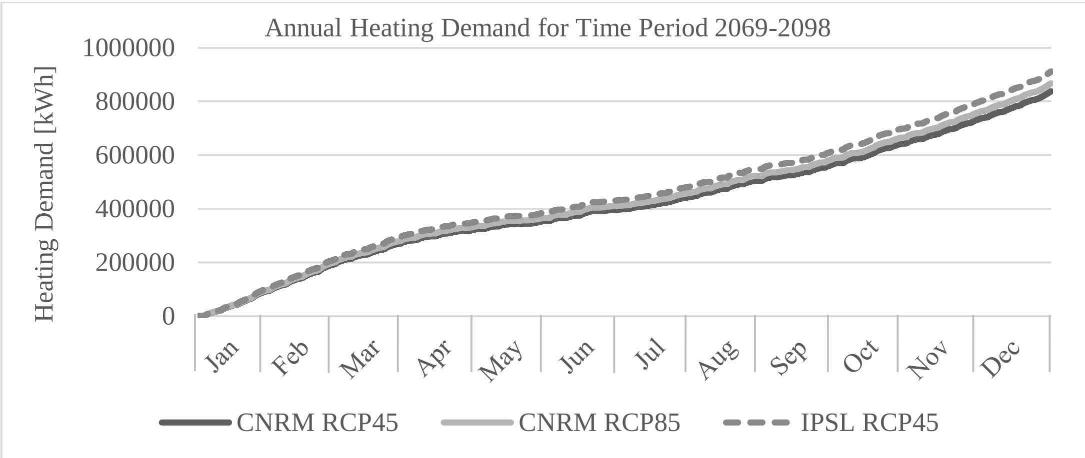

Figure 227: Annual heating demand for the wall case O in the V-building during the time period 2069-2098, for the city of Lund.

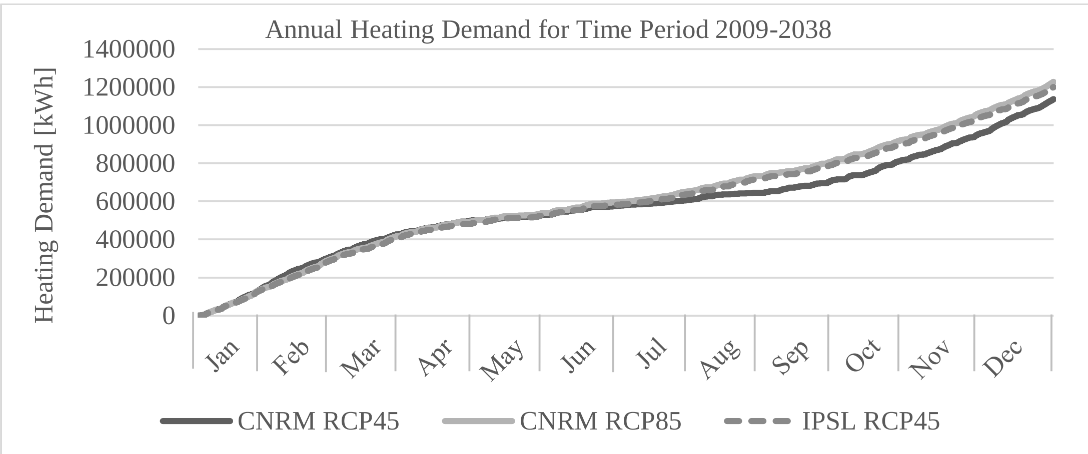

Figure 228: Annual heating demand for the roof case in the V-building during the time period 2009-2038, for the city of Lund.

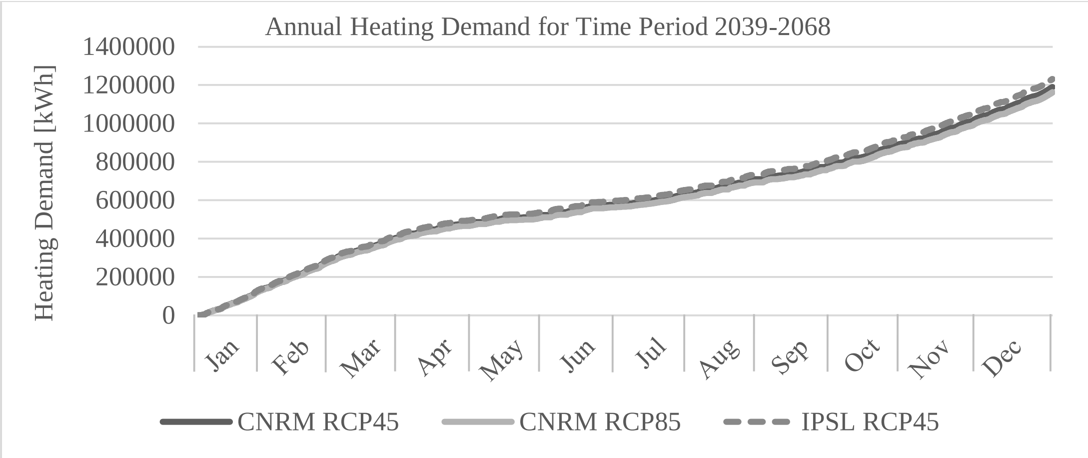

Figure 229: Annual heating demand for the roof case in the V-building during the time period 2039-2068, for the city of Lund.

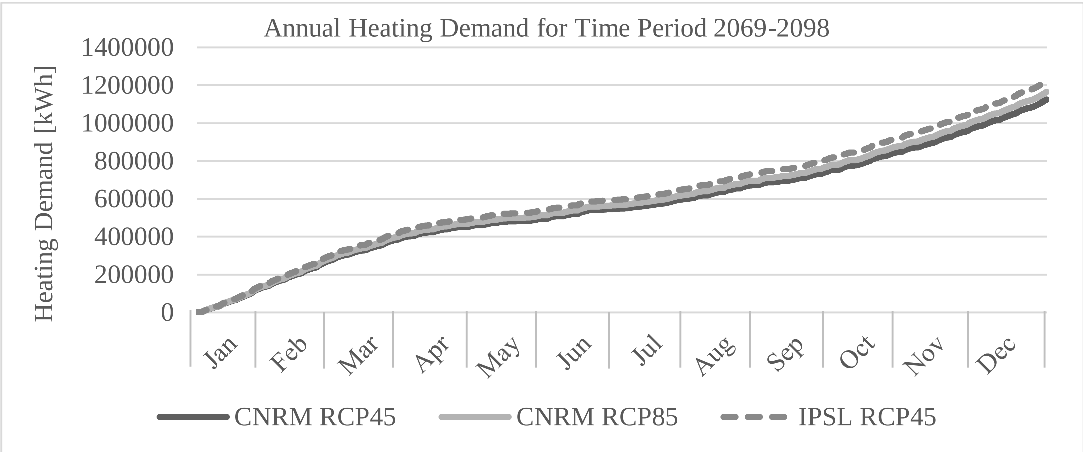

Figure 230: Annual heating demand for the roof case in the V-building during the time period 2069-2098, for the city of Lund.

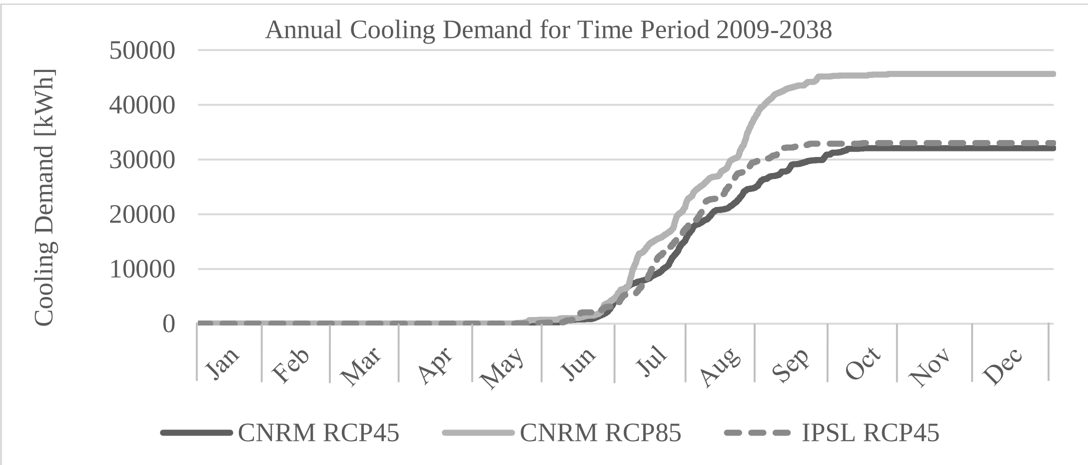

Figure 231: Annual cooling demand for the wall case H in the V-building during the time period 2009-2038, for the city of Lund.

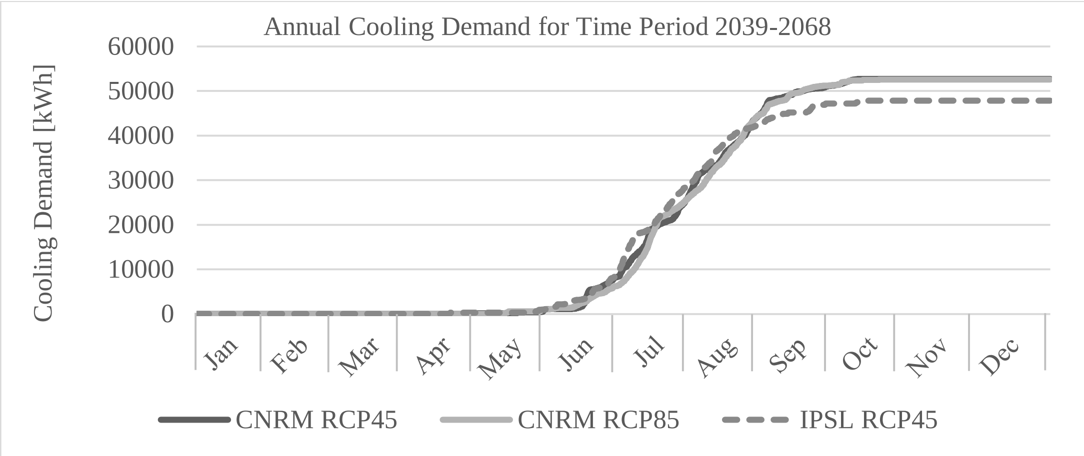

Figure 232: Annual cooling demand for the wall case H in the V-building during the time period 2039-2068, for the city of Lund.

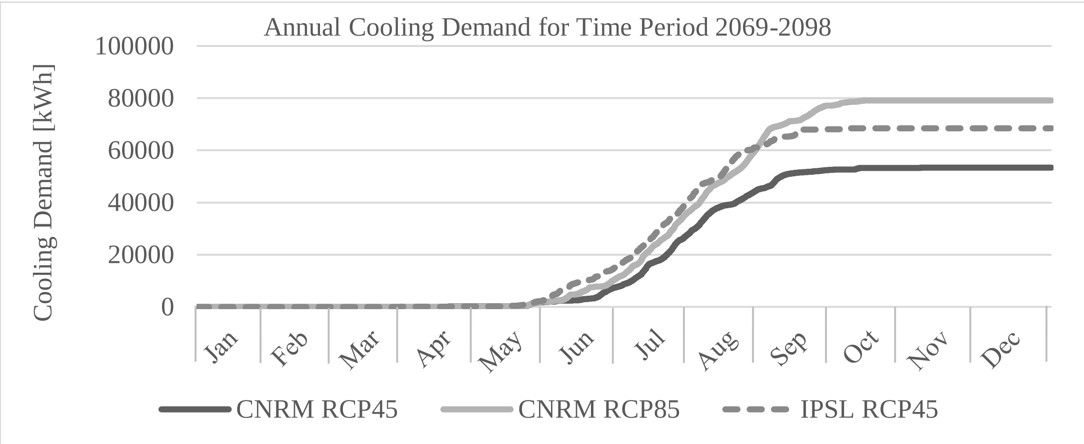

Figure 233: Annual cooling demand for the wall case H in the V-building during the time period 2069-2098, for the city of Lund.

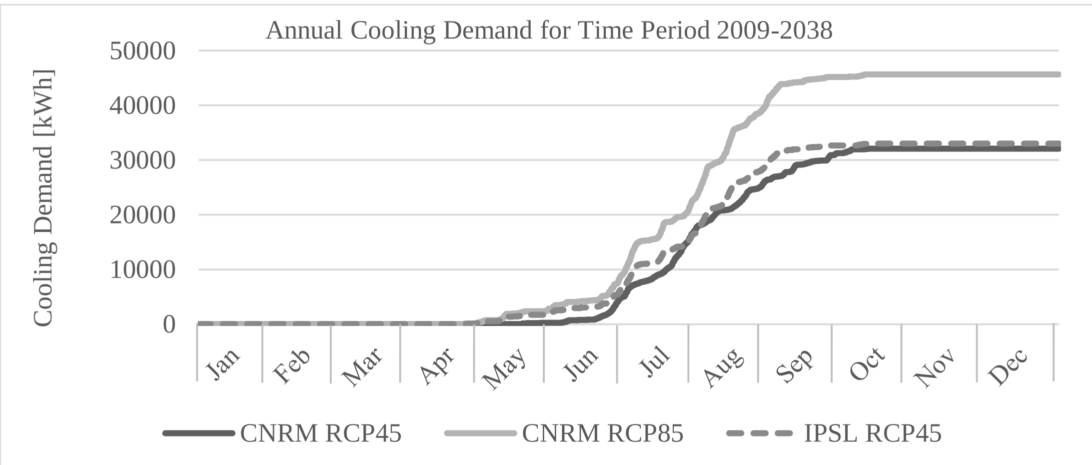

Figure 234: Annual cooling demand for the wall case N in the V-building during the time period 2009-2038, for the city of Lund.

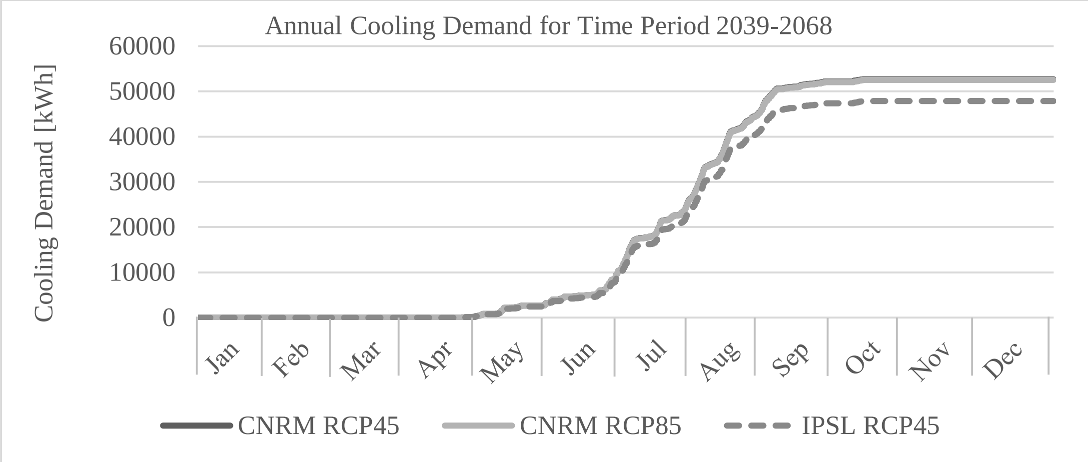

Figure 235: Annual cooling demand for the wall case N in the V-building during the time period 2039-2068, for the city of Lund.

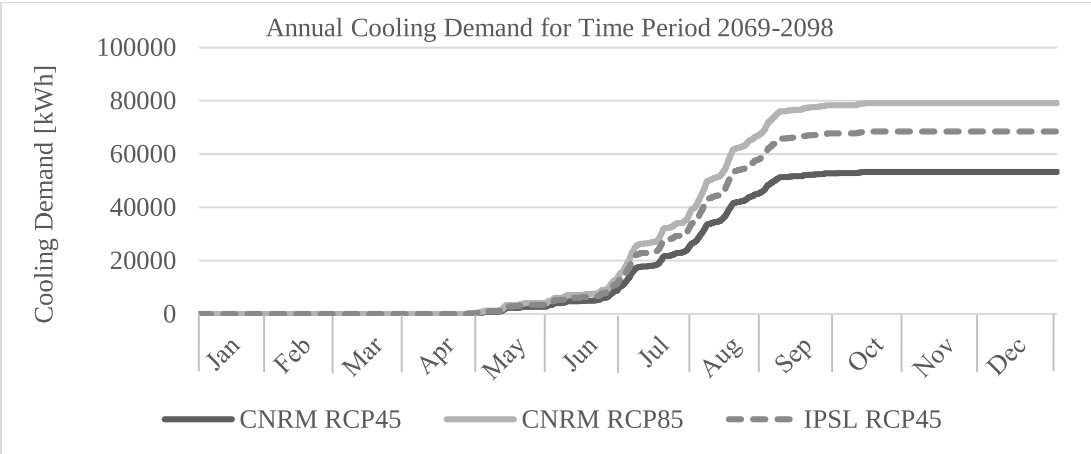

Figure 236: Annual cooling demand for the wall case N in the V-building during the time period 2069-2098, for the city of Lund.

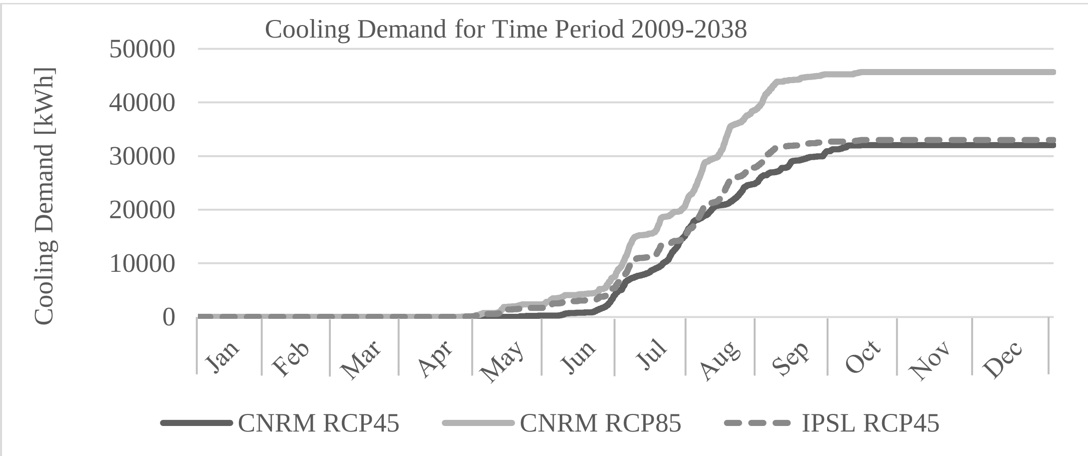

Figure 237: Annual cooling demand for the wall case O in the V-building during the time period 2009-2038, for the city of Lund.

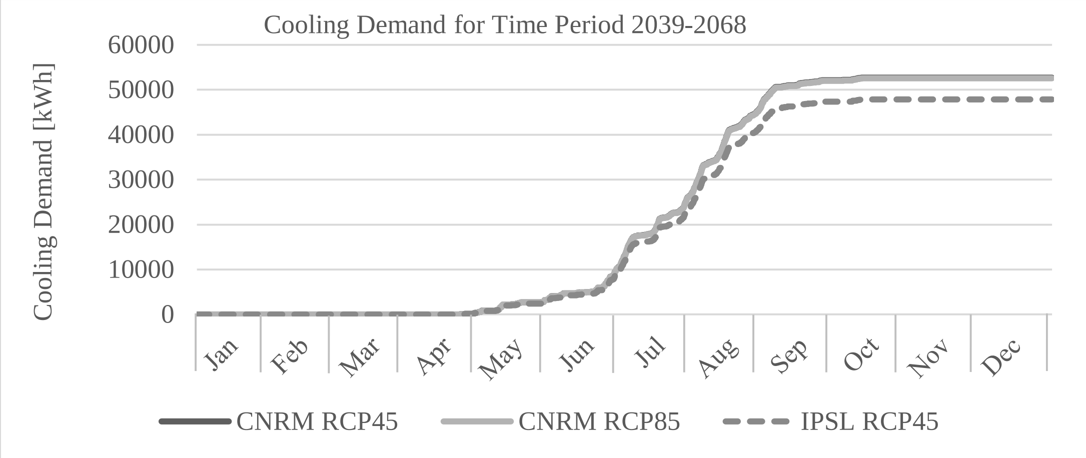

Figure 238: Annual cooling demand for the wall case O in the V-building during the time period 2039-2068, for the city of Lund.

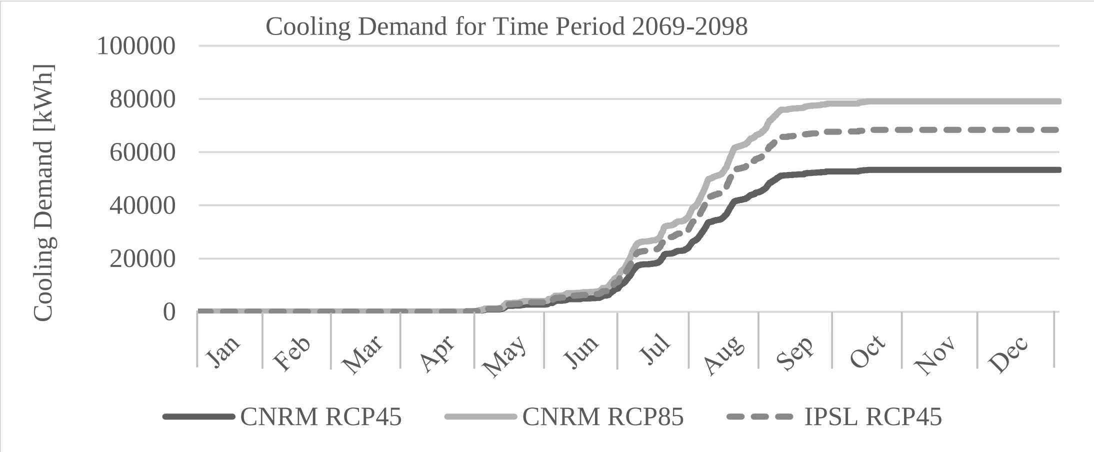

Figure 239: Annual cooling demand for the wall case O in the V-building during the time period 2069-2098, for the city of Lund.

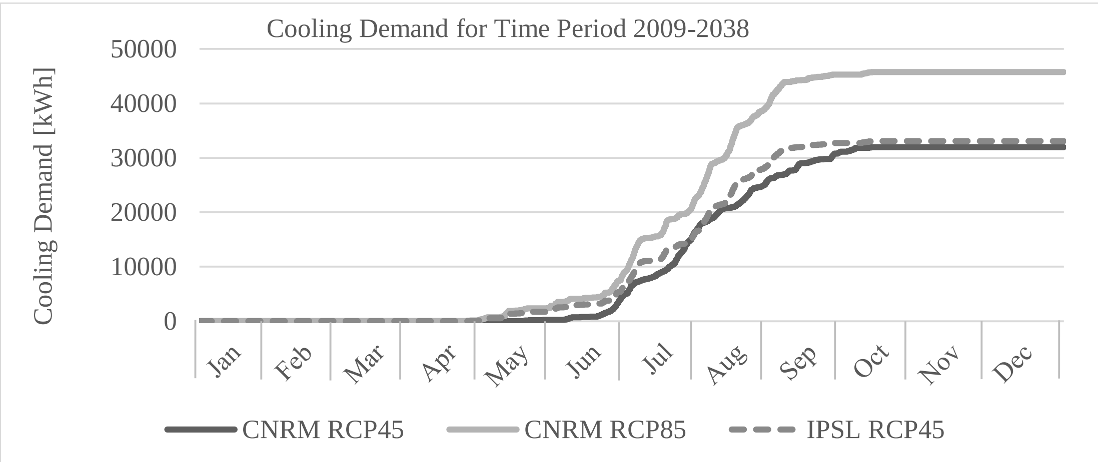

Figure 240: Annual cooling demand for the roof case in the V-building during the time period 2009-2038, for the city of Lund.

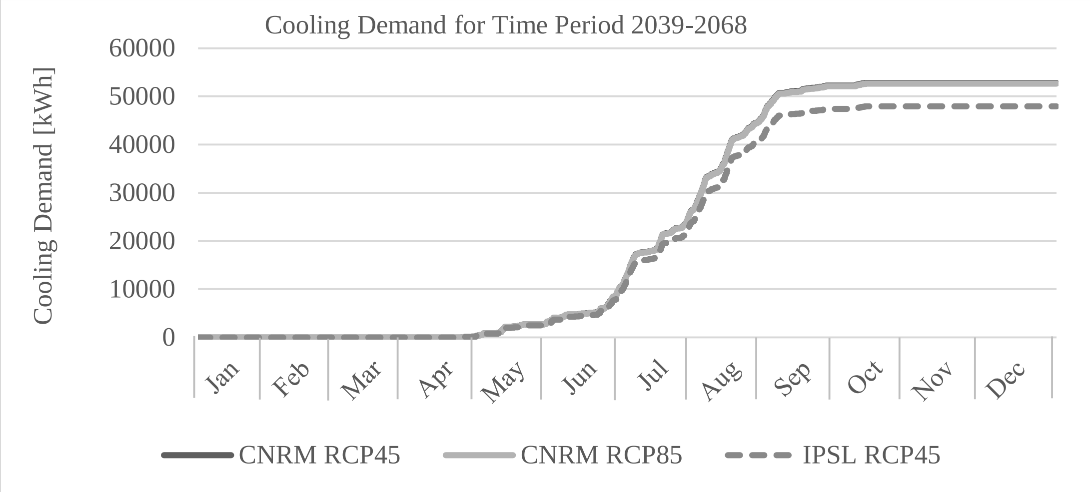

Figure 241: Annual cooling demand for the roof case in the V-building during the time period 2039-2068, for the city of Lund.

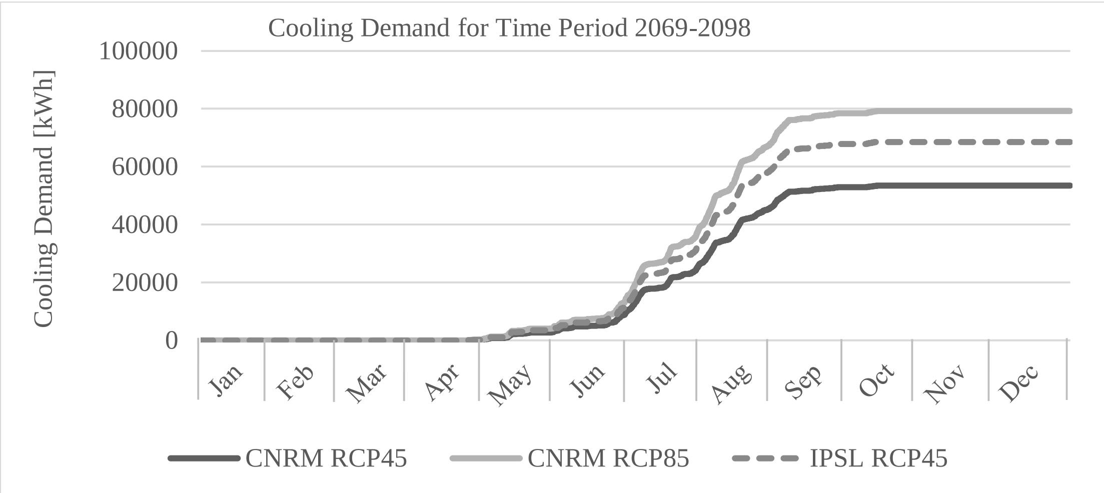

Figure 242: Annual cooling demand for the roof case in the V-building during the time period 2069-2098, for the city of Lund.

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