ASSESSMENT OF THE ENVIRONMENTAL IMPACTS, ENERGY PERFORMANCE AND ECONOMIC ASPECTS OF VARIOUS CONSTRUCTION MATERIALS

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Master thesis in Energy-efficient and Environmental Buildings
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Lund University

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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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Abstract

Increasing CO_2 emission is considered as the main reason for global warming in the world. One of the reasons for producing CO_2 is using of fossil-based materials in the construction projects. This study intends to assess the using bio-based materials instead of fossil-based materials for the thermal insulation layer of the external walls and roofs. Another focus of this project is using green concrete instead of normal concrete to save at least 30 % CO_2 emission for the foundation. The next objective of this project is applying the rectangular pre-insulated air ducting system instead of the normal steel galvanised spiral ducting system to improve the environmental impact of the HVAC system.

The study is based on a residential building having a timber structure and using concrete elements for the ground floor and foundation. The built area is 3572 m^2 in 7 floors and the project is located in Karlskrona, Sweden.

This study was performed in different sequenced steps of the quantities survey, selection of the materials, energy analysis, environmental assessment, economic analysis and future climate analysis. Selection of the materials was conducted based on the mechanical and technical properties that are matched with the BBR 26 and design's requirements. Based on the selected materials, 30 scenarios were defined and the energy simulation was performed by IDA ICE for each scenario separately. After that, the primary energy need of the project was calculated based on BBR 26 for each scenario. To investigate the environmental impacts, the Life Cycle Assessment (LCA) was performed by OpenLCA and excel files. The next step was assessing the economical aspect by the Life Cycle Costing (LCC) method. Then, by applying the Single-Point Rate (SPR) calculation, the best scenario was selected regarding the integration of primary energy number (EP_{pet}), LCA and LCC. Finally, the future climate analysis was carried out for the selected scenario to investigate the reliability of the selected scenario based on the future weather condition between 2070 and 2099.

According to the results, the scenario which includes the bio-based material (wood fiber) for the insulation, green concrete for the foundation and rectangular pre-insulated duct for the air duct system was selected as the optimum scenario. This result was based on the equal weighting factor for the EP_{pet}, LCA and LCC. In fact, this scenario demonstrated almost 15 % lower environmental impact than the scenario which is used fossil-based materials such as glass or mineral wool. On the other hand, if the economical aspect of the project is more important than the environmental aspect, the scenario with the fossil-based materials should be applied. The future climate analysis illustrated that the heating energy demand of project will be decreased during the next 50 years, while the cooling energy demand will be increased twice. Therefore, the suitable infrastructure is expected for this project to be able to support the cooling energy demand of the building in the future. Also, the CO_2 emission due to energy use of the project is almost 14 % higher from 2070 to 2099. It is basically, because of increasing the cooling energy demand in this time period.

Acknowledgments

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We also want to show our gratitude to all lecturers, coordinators and other staff at Lund University who supported us during our master education. We thank all of them for making it possible for us to study at LTH and for being there for us.

A special thanks to AFRY which trust on us to be members of this project. All the details, construction drawings and necessary documents were being ready at the time of need. This management is impossible without helping the industrial supervisors, Kim Gunnarsson and David Wargert. In addition, during the project, we learn many tips about energy simulation from David Wargert in the real project and we would like to say many thanks to him for his valuable comments during the project’s process.

Nomenclature

Abbreviation	Description
AHU	Air handling unit
A-Plan	Architectural plan
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
A_{temp}	Heated area
BBR	Boverket´s building regulations “Swedish Regulations for building works”
BOQ	Bill of quantity
BPS	Building performance simulation
CL	Cellulose
CLT	Cross-laminated timber
COP	Coefficient of performance
CO_2	Carbon dioxide
DHW	Domestic hot water
ECY	Extreme cold year
E_f	Property energy
E_{kyl}	Energy for air conditioning
EPD	Environmental product declaration
EP_{pet}	Primary energy number
E_{tvv}	Energy for hot tap water
EU	Europe Union
E_{uppv}	Energy for space heating
EWY	Extreme warm year
F_{geo}	Geographical adjustment factor
GW	Glass wool
GWP	Global warming potential
GSHP	Ground source heat pump
HVAC	Heating, ventilation and air conditioning
IDA ICE	IDA-Indoor climate and energy
LCA	Life cycle assessment
LCC	Life cycle cost

M_{toe}	Millions of tonnes of oil equivalent
MW	Mineral wool
NPV	Net present value
NRC	Normal Romanian concrete
NSC	Normal Swedish Concrete
nZEB	Net zero energy buildings
PE_i	Primary energy factor
PPM	Parts per million
PRD	Pre-insulated rectangular duct
QS	Quantity survey
RCMs	Regional climate models
RH	Relative humidity
RH_{crit}	Critical relative humidity
SDGs	United Nation’s Sustainable Development Goals
SFP	Specific fan power
SGC	Swedish green concrete
SMACNA	Sheet metal and air conditioning contractor’s national association
SPD	Spiral duct + closed-cell elastomeric foam insulation
SPR	Single-point rate
TDY	Typical downscaled year
UN	United Nation
U/P	Unit price
WF	Wood fibre
WUFI	Wärme Und Feuchte Instationär– "heat and moisture transiency"
XPS	Extruded polystyrene

Quantities and units

Sign	Description
°	Degrees
ρ	Density [kg/m³]
λ	Thermal conductivity [W/mK]
ΔT	Temperature difference [K]
ΔU	Difference in thermal conductance [W/m²K]
g-value	Solar energy transmittance [%]
K	Kelvin
°C	Degree Celsius
SEK	Swedish krona
kWh	Kilowatt-hour
kg	Kilogram
kg_{Co2eq}	Carbon dioxide equivalent in kilogram
Pa	Pascal
h	Hour
U-value	Thermal conductance [W/m²K]
λ -value	Thermal conductivity [W/mK]
W	Watt
km	Kilometre
m	meter
m^2	Squared meter
m^3	Cubic metre

Table of content

1 Introduction

Nowadays, all nations aim for reducing green gas emission, primary energy used, and depletion of natural resources that currently are the foremost mother earth's challenges since all of them are complex and cross-cutting issues.

Reference to the United Nation's Sustainable Development Goals (SDGs) and Paris Agreement commitment shows that construction and real estate have been substantial to the debates on sustainable development [2]. According to 2030 UN Agenda for Sustainable Development, construction and real estate industry could participate dramatically to achieve those ambitious SDGs by 2030, particularly at several goals. Specifically on goal 11 Sustainable Cities and Communities, goal 12 Responsible Consumption and Production, and goal 13 Climate Action [3-4]. Regarding to the Paris Agreement marked a turning point in the call to tackle global warming potential. Seizing on that momentum, swift deployment of energy-efficient and low-carbon emission solutions for the construction and real estate sector can assistance put the world on a sustainable path [5].

As per the global perspectives, the construction and real estate sector recorded around 36% of global final energy use and 39% of energy-related carbon dioxide (CO_2) emissions when upstream power generation was included on 2019 [6]. In addition, it is predicted that building stock will reach a double amount area by 2060 to be able to take in the future expected population of ten billion capita while two thirds of this population will be residence in cities [7]. In other words, by 2060 buildings sector's built area will double, adding more than 2.3E14 m^2 to the planet in new buildings construction besides that the construction processes generate around 3.73E09 metric tons of carbon dioxide (CO_2) emissions annually [5]. A further concern is the accumulating of carbon dioxide emissions for the next 30 years' life span reaching till 2050 that related to the building materials embodied carbon dioxide emissions will be roughly equivalent to the operational energy of the buildings carbon dioxide (CO_2) emissions that proofs the importance of considering in reducing embodied carbon emissions in construction material as a pressing issue. Therefore, new building stock must be designed to comply with zero-net-carbon standards to meet SDGs and Paris Agreement commitment.

The situation in Europe is not better than the rest of the world, whereas on 2019 the European construction and real estate field was responsible for about 40% of energy used and 36% of carbon dioxide (CO_2) emissions [8]. Accordingly, the 2030 climate and energy framework in European commission includes EU-wide ambitious targets and policy objectives for the period from 2021 to 2030 in three focal targets firstly, a binding target to cut greenhouse gas emissions in the EU by at least 40% below 1990 levels by 2030. Secondly, a compulsory renewable energy target for the EU for 2030 of at least minimum 32% of total final energy consumption in Europe. Finally, a headline target of at least 32.5% for energy efficiency to be achieved collectively by the EU in 2030. In absolute terms, this means that European energy consumption should not exceed 1273 M_{toe} (million tonnes of equivalent) of primary energy and/or no more than 956 M_{toe} of final total energy used [9-10]. Consequently, European construction and real estate sector has to fulfil with carbon-neutral emissions norms in the main two aspects materials and energy use in the buildings to achieve climate and energy framework's targets by 2030.

Last decades climate change adaptation importance escalated extremely in various aspects of life and pursuing the advances in computing future climatic condition, that led to the wide availability of future climate data sets which could predict the probable impacts of climate change [11]. Whereas the Impact of climate change is playing a major role in building's design that trigger the academic researchers to do more effort in this field. However, forecasting for climate change adaptation is complex since it is not easy to foresee the expected degree of warming and the step of changes [12]. This momentum led to a tremendous number of academic researchers in different construction and real estate industry aspects. Nevertheless, this study focuses on evaluating the future climate impacts in terms of building energy use and the building components performance beside the carbon dioxide (CO_2) emissions of power generation as was shown in many academic works [13-17].

This report assesses the environmental and economic impacts and fluctuation of primary energy use due to employ combination of selective construction materials in new construction located in Karlskrona, Sweden as it is shown by Figure 1. The construction materials were aimed to be assessed were the thermal insulation of building's envelope, the ready-mix concrete for building's foundation and air ducting systems. Moreover, in light of future climate analysis, building energy simulation was conducted for the optimum materials combination which has minimum values of carbon dioxide (CO_2) emissions and costs based on files represented climate predictions of the last three decades for current century (2070-2099). The method for synthesizing future climate predictions into a typical downscaled year (TDY), extreme cold year (ECY) and extreme warm year (EWY) that was provided by Nik [11] was employed and resulted in a total of three climate files for Karlskrona, Sweden.

Figure 1: Geographical locations of the case study

1.1 Objectives

In this project, 3 building materials comprised of thermal insulation for the exterior walls and roofs, ready-mix concrete for the foundation and air ducting system were assessed. 24 scenarios were created based on the permutations of different material.

Another objective was to improve the selected scenario to achieve a Zero-CO_2 emission construction. It means that in total, there were 30 scenarios in this study.

The last objective of this study was to carry out the future climate analysis based on the extreme climate data from 2070 to 2099 to make sure that the project will be feasible and functional in terms of primary energy use, environmental impacts and the costs.

1.2 Research Questions

Based on the objectives the main research questions in this work are:

- Which bio-based material is suitable to achieve the goal of the project in terms of Zero-CO_2 emission for the building thermal insulation? The aim is to compare 2 fossil-based insulations to 2 bio-based insulations.
- Which types of concrete is suitable to decrease the environmental impacts of the project? The green ready-mix concrete needs to be compared with the normal ready-mix concrete.
- Which type of duct performs better in terms of LCA, LCC and energy use? A rectangular pre-insulated duct is assessed to show the differences with the normal steel galvanized spiral duct.
- What are the effects of selected materials on the primary energy use of the building based on BBR26? Do they all meet the BBR requirements?
- What are the environmental impacts of each scenario in terms of Global Warming Potential (GWP) category? Based on the client's requirement, GWP is selected as the environmental impact category.
- Which scenario is the best in terms of integration of LCA, LCC and Primary Energy Use? The Single-point Rate (SPR) calculation needs to be performed with different weighting factors.
- What is the performance of the optimum scenario based on future climate data in terms of Energy performance and environmental impacts? The future climate analysis needs to conducted based on EWY, ECY and TDY.

1.3 Workflow

The workflow in the present study is as demonstrated in Figure 2. It starts with a literature review to know the latest research and achievements about the environmental impacts of the materials and methods of LCA. The data collection phase was performed by investigating the architectural plans, structural plans and HVAC plans. Moreover, there are other descriptions about the project that were provided by the responsible company to add to the data collection phase.

Different construction materials were chosen in the scenarios definition phase and the EPDs (Environmental Product Declarations) of selected materials were investigated in parallel. The energy analysis was performed by IDA ICE and then, the results from IDA ICE were imported to an excel file to calculate the primary energy use of the building based on BBR26. OpenLCA was used to obtain the environmental impacts of each scenario, regarding transportation and energy use. Also, for one of the materials, the EPD was produced by OpenLCA. To find the economical aspect of the scenarios, the LCC (Life Cycle Cost) calculation was performed by using an excel sheet based on net present value approach (NPV). The assessment and comparison phase were carried out to find the best scenarios in terms of integration LCA, LCC and primary energy use. The SPR calculation was accomplished in this phase. Finally, future climate analysis was fulfilled regarding future climate data set. The extreme climate data was applied for the future climate analysis and the best scenario which was selected in the previous phase was assessed.

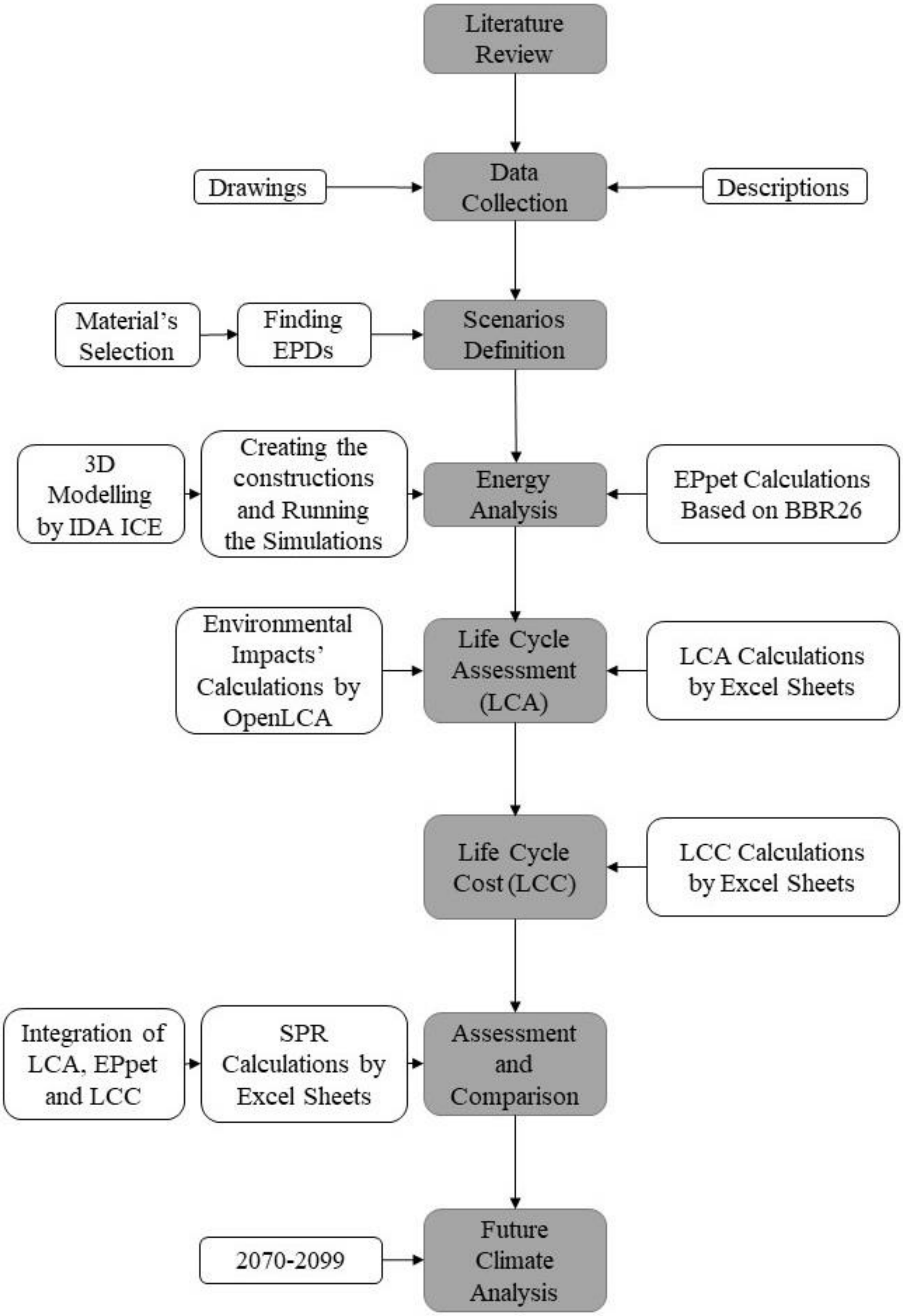

Figure 2: Graphical abstract of project process

1.4 Limitations

The study is investigating a residential building as it was applied in a real project. This project is carried out by a company which is named AFRY in Malmö as project manager in conjunction with many engineering services firms as the design team. All conclusions drawn in this report are based on the findings of the case study.

The building performance as well as energy use, LCA and LCC of the case study were validated based on the data provided by the companies, building owners and supplementary data from academic studies. Conclusions may not be applicable to other cities and buildings with different applications as the study was performed for a residential project located in Karlskrona.

The assumptions were considered based on the realistic values to be useful for the client and company to be used later. Due to lack of IDA ICE weather data for Karlskrona, the weather data of the closest city was used, which is Ronneby-Kallinge in 30 km distance. In addition, the factory of the ready-mix concrete should be close (Maximum 45 minutes) to the project site to avoid degradation of the concrete at the truck mixer, while there was no EPD from the factories which were close to the project site. Therefore, the ready-mix concrete factories were selected among the factories in EPD database. It was assumed that the transportation distance from the concrete factory to the project site is 45 minutes (almost 60 km with a speed of 80 km/h).

2 Methodology

The following chapter gives an overview of the methodology that was developed in order to tackle the study. The chapter is divided into seven sections, starting with the general information about the project. Secondly, the materials and scenarios which were used in this study are introduced. Thirdly, the Energy Analysis section provides an explanation of the methods and energy simulation software. Also, important input parameters are disclosed in this section. In the fourth and fifth sections, LCA inputs, LCC inputs and assumptions are explained respectively. Section 6, explains the methods that the results of LCA, LCC and primary energy use were integrated. Finally, in the section 7, the method of future climate analysis is expressed.

The study is based on a case study that includes one building block among three building blocks of a residential building as it was applied in a real project. Regarding the time limitation, just one of these blocks was selected and the results can be correlated for other two blocks. The bigger building block was selected as the case study and basically, because the weather data, the location, the materials, function and the structure are the same. In addition, the main logic and procedure of the designing structures, HVAC systems and architectural aspects are the same for all these blocks.

2.1 Project's information

Kilström's project is located in Karlskrona. It consists of three residential building blocks, a restaurant and a garage. This thesis refers to Block A, which is shown in figure 3. Block A consists of 7 floors with a built area of 3572 m^2. The ground floor comprises residential apartments, stores and a technical room. It is attached to an unheated garage. The remaining floors are residential apartments.

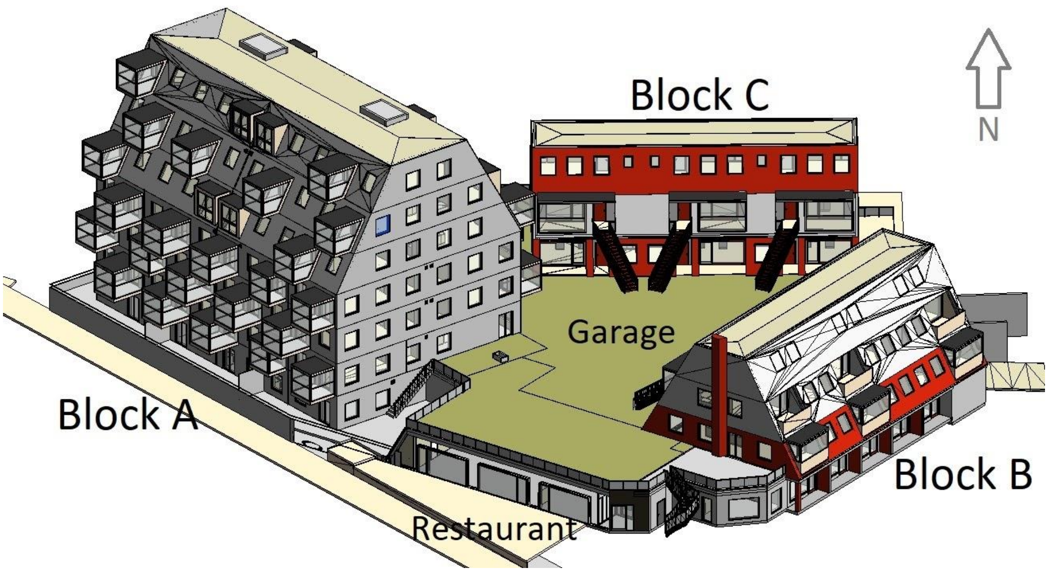

Figure 3: 3D model of the project

2.2 Materials and Scenarios

To conduct the project, four types of thermal insulation, three types of ready-mix concrete and 2 types of air ducting system were considered to provide different scenarios with the permutations and combinations of them.

2.2.1 Ready-mix concrete selection

To select the ready-mix concrete, the structural plans were investigated to find the properties of the concrete for the foundation which the building was designed based on. Table 1, illustrates the properties of the ready-mix concrete for this project.

Table 1: Mechanical properties of the ready-mix concrete

Exposure Class	Compressive Strength Class	Water to Cement Ratio
XD2	C30/37	< 0.5

Based on table 1, three types of ready-mix concrete were selected. All of them have a verified EPD during the next 5 years. Table 2, shows the properties of the different types of ready-mix concrete that were employed in this study. The green concrete brings the lower CO_2 emission impact and it was chosen to show the difference of environmental impacts of the green concrete in comparison with the normal concrete.

Table 2: Employed ready-mix concrete characteristics in this study

Type of concrete	Compressive Strength class	Density / (kg/m^3)	Water to Cement Ratio
Normal Swedish Concrete (NSC)	C30/37	2394	< 0.5
Normal Romanian Concrete (NRC)	C30/37	2300	< 0.5
Swedish Green Concrete (SGC)	C32/40	2412	< 0.5

2.2.2 Thermal insulation selection

Four different thermal insulations were selected to conduct into the project. Based on the BBR 26, the average of the U-value of the building should not exceed 0.4 W/m^2K and the thermal insulations were selected based on this criterion. Two of them were bio-based with the negative CO_2 emission impact to make a comparison with two others that are fossil-based with positive CO_2 emission impact. The external walls and the roofs are considered for this evaluation. Table 3, lists the properties of thermal insulations that were applied in this study.

Table 3: Employed thermal insulations properties in this study

Type of thermal insulation	**λ-Value / (W/(m·K))**	**Density / (kg/m^3)**
Glass wool (GW)	0.035	20
Mineral Wool (MW)	0.035	23
Wood Fiber (WF)	0.044	165
Cellulose (CL)	0.039	50

Due to using bio-based insulation the moisture risk should be assessed. To do the numerical analysis for calculating the relative humidity (RH) and temperature (T) for each layers of the wall, WUFI was used. In the next step, VTT model [18] was applied to use the critical relative humidity (RH_{crit}) to assess the mould growth index and the risk of mould [14-15]. This assessment was performed by MATLAB.

The results for Mineral wool, Wood fiber and Cellulose shows that the mould growth indexes were close together and all of them are within the safe margin. It means that there is no risk due to using bio-based insulation rather than fossil-based insulation in case of applying a suitable vapor retarder. The more information and graphs about the mould growth index and hygrothermal performance are in the appendix 6.4 of this report.

2.2.3 Duct selection

Regarding the HVAC plans, each apartment has a dedicated Air Handling Unit (AHU) and each one connected to the four duct systems comprised of supply air, exhaust air, fresh air and return air. Based on the HVAC plans, the type of duct which was employed for four duct systems is the same with different sizes and insulation thickness. In this case, the selected duct's types were investigated for all the duct systems in this project. In addition, two different shapes of the duct consist of rectangular pre-insulated duct and spiral duct were assumed with the same pressure losses and air velocities as 1.2 Pa/m and 2.5-3.5 m/s respectively based on ASHREA 55 and SMACNA [20] [21]. The differences are in the λ-Value and duct surface area. Table 4, shows two types of the duct used for this study.

Table 4: Employed ducts in this study

Type of duct	**λ-Value / (W/(m·K))**
Pre-insulated rectangular duct (PRD)	0.021
Spiral duct + closed-cell elastomeric foam insulation (SPD)	0.040

2.2.4 Scenarios

Permutations and combinations of the selected materials were performed to generate different scenarios for this study. For all scenarios, energy analysis, LCA and LCC were carried out separately. There were 24 scenarios in the first step of this study that are listed in table 5. In the next step, 6 more scenarios will be added to investigate the improved scenarios.

Table 5: Proposed scenarios

Scenario	Insulation	Duct Type	Concrete Type
Scenario 01	GW	PRD	SGC
Scenario 02	MW	PRD	SGC
Scenario 03	WF	PRD	SGC
Scenario 04	CL	PRD	SGC
Scenario 05	GW	SPD	SGC
Scenario 06	MW	SPD	SGC
Scenario 07	WF	SPD	SGC
Scenario 08	CL	SPD	SGC
Scenario 09	GW	PRD	NRC
Scenario 10	MW	PRD	NRC
Scenario 11	WF	PRD	NRC
Scenario 12	CL	PRD	NRC
Scenario 13	GW	SPD	NRC
Scenario 14	MW	SPD	NRC
Scenario 15	WF	SPD	NRC
Scenario 16	CL	SPD	NRC
Scenario 17	GW	PRD	SGC
Scenario 18	MW	PRD	SGC
Scenario 19	WF	PRD	SGC
Scenario 20	CL	PRD	SGC
Scenario 21	GW	SPD	SGC
Scenario 22	MW	SPD	SGC
Scenario 23	WF	SPD	SGC
Scenario 24	CL	SPD	SGC

2.3 Energy Analysis

The energy analysis was conducted in 2 steps. First, the energy simulation was carried out to determine the annual energy need for each energy type including space heating, cooling, domestic hot water (DHW) and facility energy. Then, the primary energy calculation was performed to check the energy use of the building based on BBR 26 [22]. These steps were carried out for all the scenarios separately.

2.3.1 Energy simulation

The energy simulation was performed by IDA ICE 4.8. First of all, the 3D energy model was built based on the interior dimensions of the building. Figure 4, shows the 3D energy model which was produced by IDA ICE.

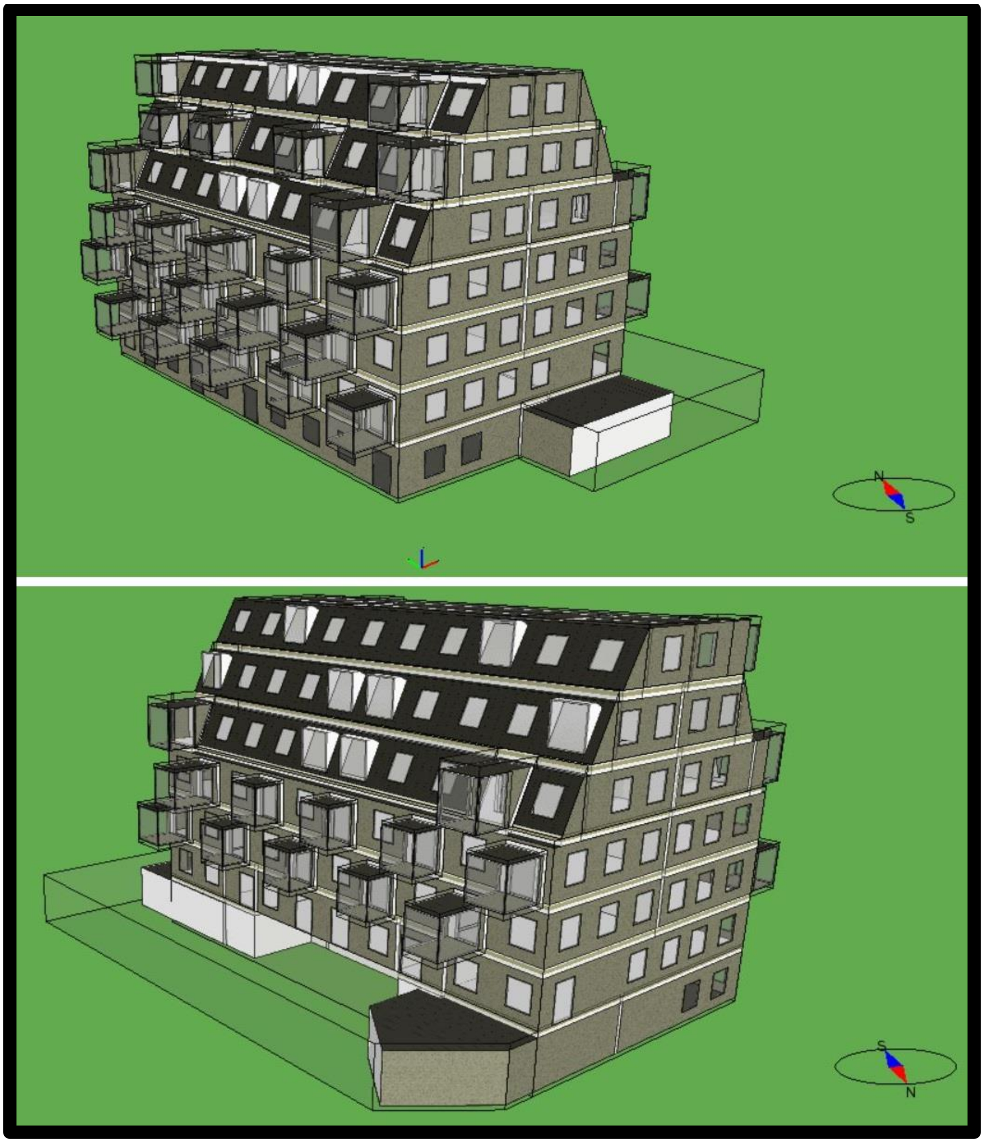

Figure 4: 3D Energy model in IDA ICE

Then, the construction of the external walls, internal walls, roofs, ceilings, ground floor, windows and doors were defined for the simulation software. Table 6, illustrates the construction properties of the base case of the building. The base case means the current design of the building which was performed by the responsible company.

Table 6: Construction properties

Element	**Thickness and material / mm**	**λ – Value / (W/(m·K))**	**U – Value / (W/(m² ·K))**	**Remark**
Ground floor slab	200 Concrete 300 XPS 150 Macadam	1.7 0.035 1.3	0.08	The ground resistance is included
Balcony floor	270 Concrete	1.7	3.04	Based on A-plan
Internal floor (Ceiling)	85 CLT 200 air gap 200 CLT	0.13 0.17 0.13	0.28	Based on A-plan
Roof	300 Insulation 200 CLT	0.035 0.13	0.1	Based on A-plan
Roof of stores	260 Insulation 320 Concrete	0.035 1.7	0.13	Based on A-plan
Inclined roof	200 Insulation 140 CLT	0.035 0.13	0.14	Based on A-plan
Balcony Roof	100 Insulation 100 CLT	0.035 0.13	0.26	Based on A-plan
Internal wall (CLT)	95 Insulation 140 CLT	0.035 0.13	0.25	Based on A-plan
Internal wall (Between two apartment)	200 Concrete	1.7	3.47	Based on A-plan
Internal wall (Shared with the garage)	95 Insulation 200 Concrete	0.035 1.7	0.33	Based on A-plan
External wall (CLT)	140 CLT 200 Insulation	0.13 0.035	0.14	Based on A-plan
External wall (Concrete)	150 Concrete 200 Insulation	1.7 0.035	0.17	Based on A-plan
External wall for stores	250 Concrete	1.7	3.15	Based on A-plan
Window	-	-	0.9	g-value: 0.55
Widow doors	-	-	0.9	g-value: 0.55

Furthermore, to calculate the annual energy use the internal loads have to be defined for the software. All the assumptions in the energy analysis phase were based on BEN 2 and BSRIA standards [23]. The assumed internal loads for each zone are demonstrated by table 7.

Table 7: Internal loads for each zone

Type of zones	Lighting	Occupants	Equipment
Residential zone	5 W/m^2 00:00-06:00 - 30% 06:00-18:00 - 50 % 18:00-24:00 - 100 %	0.022 person/m^2 Occupied schedule: 17:00-07:00	10 W/m^2
Stair case	8 W/m^2 4000 h/year (Entrance) 1300 h/year (Others)	Unoccupied	0 W/m^2
Technical Room	4 W/m^2 300 h/year	Unoccupied	20 W/m^2
Store	4 W/m^2 300 h/year	Unoccupied	0 W/m^2
Balcony & Garage	Unconditioned zone		

To include the effects of HVAC system the set-points need to be determined for the zones. Table 8, lists the set-points that were employed for this study.

Table 8: Set-points

Type of zones	[1]Heating Set-points Temperature / °C	[1]Cooling Set-points Temperature / °C	Air Flow	Relative Humidity / %	Level of CO_2 / PPM
Residential zone	21℃ (Based on BEN 2)	24 ℃ ASHRAE 55	0.35 l/s·m^2 and 7 l/s·person, Basic air flow 0.7 l/s·m^2, force ventilation, Summer time (mid-April till mid-September) (Continuously air flow, Based on HVAC-consultant)	40-60	400-1000
Stair case	18 ℃ (Based on HVAC-consultant)	26 ℃ ASHRAE 55	0.35 l/s·m^2 , Basic air flow (Continuously air flow, Based on HVAC-consultant)	40-60	400-1000
Technical Room	18 ℃ (Based on HVAC-consultant)	26 ℃ ASHRAE 55	0.35 l/s·m^2, Basic air flow (Continuously air flow, Based on HVAC-consultant)	40-60	400-1000
Store	18 ℃ (Based on HVAC-consultant)	26 ℃ ASHRAE 55	0.35 l/s·m^2, Basic air flow (Continuously air flow, Based on HVAC-consultant)	40-60	400-1000
Balcony & Garage	Unconditioned (Un-heated)				

[1] Thermostat dead band temperatures = ± 2 °C

In fact, the heating energy demand was covered by the ground source heat pump (GSHP). The cooling energy demand was achieved with the same boreholes and water pump to circulate the cold water from the ground to the technical room. Therefore, this project used the free cooling energy. Table 9, shows the details and principle of HVAC systems were applied in this project.

Table 9: HVAC systems details

Heating Principle	The GSHP was employed as the heating energy source using 17 boreholes. The under-floor heating was applied as space heating of the inside of the apartment (except bathrooms) and the radiator was used for other places. 90% of the heating demand was covered by GSHP and 10% of that was covered by the electrical boiler. The COP of GSHP is 4.13 for space heating and DHW. As the safety factor, the COP is assumed 3.5 in the simulation. Distribution losses are assumed 4% of space heating energy demand. Average hot water use as Domestic Hot Water (DHW) is 75 L/day·Person.
Cooling Principle	The cooling was achieved via air treatment. The same water pump which was used for the water circulation of the boreholes was employed for the cooling as well. The project used free cooling energy for cooling demand. The energy consumption of the pump is 1 kWh/m^2 for heating and cooling and it works 100% of the time.
Ventilation	Each apartment had an individual AHU with rotatory heat exchanger and an efficiency of 83% for air heat recovery. The SFP of the ventilation system was 1.5 kW/m^3/s. The supply air temperature was 20 °C (when the ambient temperature degree was minus) and 18 °C (when the ambient temperature degree is higher than zero). Air Ducts losses were assumed as 4 kWh/m^2· year.

In addition, there were other assumptions and considerations for energy simulation that are listed in table 10.

Table 10: Other assumptions and considerations for energy simulation

Elevator	The energy use was 50 kWh/apartment per year for each elevator to work. For the lightening of elevators, the energy use was 330 kWh/elevator per year. There were two elevators in this building.
Lighting of outside area of the building	The electricity use for each building entrance was assumed 20 W and it was turned on for 4000 h/year.
Thermal bridge	25% of heat transmission loss
Infiltration	0.3 l/s·m^2 at pressure 50 Pa

2.3.2 Primary energy number (EP_{pet}) calculation

To assess the energy use of the building, the primary energy use of the building was calculated based on BBR 26 [22]. According to BBR 26, the free energies such as free cooling or free heating do not need to take into account of primary energy calculation. Also, there were some requirements to be considered which are demonstrated in table 11.

Table 11: BBR requirements for this project

Geographical adjustment factor, F_{geo}	0.9	BBR 26, Table 9:2c
Primary energy factor, PE_i	1.6	BBR 26, Table 9:2b
Average of U-Value / (W/(m^2 ·K))	0.4	BBR 26, Table 9:2a
Primary energy number, EP_{pet} / (kWh/(m$^2_{Atemp}$ · year))	85	BBR 26, Table 9:2a
Installed electric input for heating /kW	90.55	BBR 26, Table 9:2a $4.5 + 1.7 \cdot (F_{geo} - 1) + (0.025 + 0.02(F_{geo} - 1)) \cdot (A_{temp} - 130)$
A_{temp} /m^2	3572	The area enclosed by the inside of the building envelope of all stories including cellars and attics for temperature-controlled spaces are intended to be heated to more than 10°C.

The primary energy use was calculated by the formula 1, based on BBR 26.

$$EP_{pet} = \frac{\sum_{i=1}^{6}\left(\frac{E_{uppv,i}}{F_{geo}} + E_{kyl,i} + E_{tvv,i} + E_{f,i}\right)}{A_{temp}} \quad \text{kWh/(m}^2_{Atemp} \cdot \text{year)} \qquad (1)$$

A_{temp}	Air-conditioned area		
E_{uppv}	Energy for space heating, kWh/(m$^2_{Atemp}$ · year)	E_{kyl}	Energy for cooling, kWh/(m$^2_{Atemp}$ · year)
E_{tvv}	Energy for hot tap water, kWh/(m$^2_{Atemp}$ · year)	E_f	Property energy, kWh/(m$^2_{Atemp}$ · year)
PE	Primary energy factor	F_{geo}	Geographical adjustment factor

2.4 Life Cycle Assessment (LCA)

The LCA was carried out based on sustainability of construction works standards EN 15804 / EN 15978 and EU-Model for Life Cycle Assessment of Building [24]. First, the quantity survey (QS) was conducted to calculate the amount of materials that were used in the project. After that, the EPDs were investigated to know the values of the environmental impacts of each material. Finally, the environmental impact calculations were accomplished by using OpenLCA and an excel file. This process was carried out for each scenario individually.

2.4.1 Quantity Survey

The quantity survey (QS) was conducted for the ready-mix concrete in the foundation, the ducts and the thermal insulation of the external walls and roofs. Actually, in this project, there are two types of concrete which were used. First, is the ready-mix concrete which was utilized for the foundation and footings of the load-bearing elements. Second, was the prefabricated slab which was used for the walls, ceilings and ground floor.

The QS for the concrete was conducted for the ready-mixed concrete of the foundation and footings based on the structural plans. Moreover, the architectural plans were investigated to calculate the amount of thermal insulations for the extremal walls and roofs. The insulation of the internal walls was not considered in this study because they were mostly used as acoustic insulation. The insulation of the foundation was XPS and the type of that was different from the insulation of the external walls. To conduct the QS for the ducts the HVAC plans were surveyed and all the ducts and their insulation materials in this project were taken into the account.

2.4.2 Environmental product declaration (EPD)

For all the materials except the spiral duct, the EPDs were downloaded from the confirmed databases [25-33]. To produce the EPD for the spiral duct, two steps were considered. First, the environmental impact of producing the hot-rolled galvanize coil from the raw material was calculated by OpenLCA. Then, the electrical energy use of galvanize coil fabrication to the duct was added to the calculation. The amount of needed electricity use of fabrication of galvanize coil to the duct shape was assumed based on the document from a duct producing company which is name Lindab [34].

2.4.3 Environmental impacts calculations

Regarding the requirements of the client the Global Warming Potential (GWP) was considered as the environmental impact category for this project. Consistent with that, the CO_2 emission of each material was extracted from the EPDs to use for the later calculations. It belonged to modules A1-A3 as the stages of the environmental impact. Also, module A4 was included in the calculations to find the CO_2 emission due to the transportation of the material from the factory to the project site. Table 12, shows the travel distance of each factory to the project's site.

Table 12: Travel distance between the factories and the project's site

Material	Travel distance / km	Country of origin
Glass wool insulation	224	Sweden
Mineral wool insulation	1717	Sweden
Wood fibre insulation	1390	Germany
Cellulose insulation	309	Belgium
Normal Swedish Concrete	60	Sweden
Normal Romanian Concrete	60	Romania
Swedish Green Concrete	60	Sweden
Pre-insulated rectangular Duct	1735	Italy
Galvanized steel spiral Duct	540	Sweden
Spiral duct insulation	854	Germany

In addition, the CO_2 emission due to operation energy (module B) of the building for 50-year building life span was calculated by OpenLCA. Table 13, illustrates the assumptions were employed during the environmental impact calculation by OpenLCA.

Table 13: Assumptions and considerations for the environmental impacts calculation by OpenLCA

Provider for Electricity	Electricity mix, consumption mix, at consumer, AC. 230V, SE
Provider for Transportation	Lorry transport, Euro 0, 1, 2, 3, 4 mix, 22 t total weight, 17.3 t max payload - RER
Impact Assessment Method	CML 2 baseline 2000
Normalization and Weighting Set	West Europe, 1995 - CML 2 baseline 2000
Calculation Type	Quick Results
Functional Unit	Cubic metre (m^3)
Life Span	50 years

2.5 Life Cycle Costing (LCC)

To perform the economic analysis of the scenarios, LCC calculations were carried out. There were two main costs that were considered in this study. First, was the initial cost and second was the running costs. The initial costs comprised of the costs for the purchasing raw materials, transportation costs, labour costs and installation costs. The running costs retained the cost for the maintenance and energy use costs. Table 14, illustrates the unit prices that were employed in this study. It is also worth mentioning that the unit prices were achieved by the inquiries from the suppliers and extracting from sektionsfakta sources [35].

Table 14: Proposed material unit prices

Material	**Unit**	**Unit Price / SEK**
Glass wool insulation	m^3	552
Mineral wool insulation	m^3	924
Wood fibre insulation	m^3	1687
Cellulose insulation	m^3	911
Normal Swedish Concrete	m^3	2513
Normal Romanian Concrete	m^3	2061
Swedish Green Concrete	m^3	3091
Pre-insulated rectangular duct	m^2	132
Steel galvanized spiral duct	m^2	399
Insulation of spiral duct	m^2	396
Electricity price	kWh	1.2

The costs for the labour and installation were considered as 3 % of the material prices. Also, the costs for the repairs and maintenances were assumed as 2 % of the material prices. To perform the LCC analysis the Net Present Value (NPV) were calculated for each scenario based on formula 2 [36]. This formula is to calculate the geometric gradient series.

$$P = A_1\left(\frac{1-(1+g)^{N}(1+i)^{-N}}{i-g}\right) \qquad \text{SEK} \qquad (2)$$

P	Present worth, SEK
A_1	First year worth, SEK
N	Life span, year
g	Growth rate, %
i	Interest rate, %

Table 15, lists the assumptions that were used to calculate the NPV based on formula 2.

Table 15: Assumptions of NPV calculations

Maintenance growth rate / %	**Electrical energy growth rate / %**	**Interest rate / %**	**Life span / Year**
1.5	2	-0.24	50

2.6 Integration of EP_{pet}, LCA and LCC

The main goal of this study is to find the best scenario in terms of EP_{pet}, LCA and LCC at the same time. In another word, the integration of EP_{pet}, LCA and LCC was performed for each scenario based on the Single-Point Rate (SPR) method. Regarding this method, the weighting factors were defined for EP_{pet}, LCA and LCC to determine the importance of each of them in comparison with each other. In this step, 4 options were investigated to check the effect of various weighting factor on the final results. Table 16, shows the options that were considered for the SPR calculations.

Table 16: Weighting factors for different options

Options	**Weighting factors**		
	EP_{pet}	**LCA**	**LCC**
Option 01	33 %	33 %	33 %
Option 02	**40 %**	30 %	30 %
Option 03	30 %	**40 %**	30 %
Option 04	30 %	30 %	**40 %**

2.7 Future Climate Analysis

In the final step, the future climate analysis was executed to evaluate the energy use and the environmental impacts of this project in the future. The best scenario was chosen based on SPR calculations and the energy simulations were accomplished based on three future weather data sets for that. Three different climate data sets, including Typical Downscaled Year (TDY), Extreme Cold Year (ECY) and Extremely Warm Year (EWY) were applied in this study. These climate data sets have been synthesized from Regional Climate Models (RCMs) and they were produced for a specific time period from 2070 to 2099. More details about synthesizing the representative weather files are available in [11] while the reader can learn more about the details of synthesizing weather files from RCMs in [36-39].

Figure 5, shows the hourly climate data sets for Karlskrona for a period of 30 years. TDY graph shows the most probable dry-bulb temperature that this city will experience from 2070 to 2099. EWY and ECY are the extreme climate data sets that the probability of occurring them is very rare in the future. In other words, to analyse the energy use and the environmental impact the comparison of the current weather data of Karlskrona with the TDY is considered. While EWY and ECY data sets are applicable for sizing heating and cooling systems capacities as peak loads in this period of the future. The environmental impact calculations were carried out by OpenLCA to calculate the CO_2 emissions due to energy use for 50 years of building life span. The assumptions of these environmental impact analysis were the same as table 13.

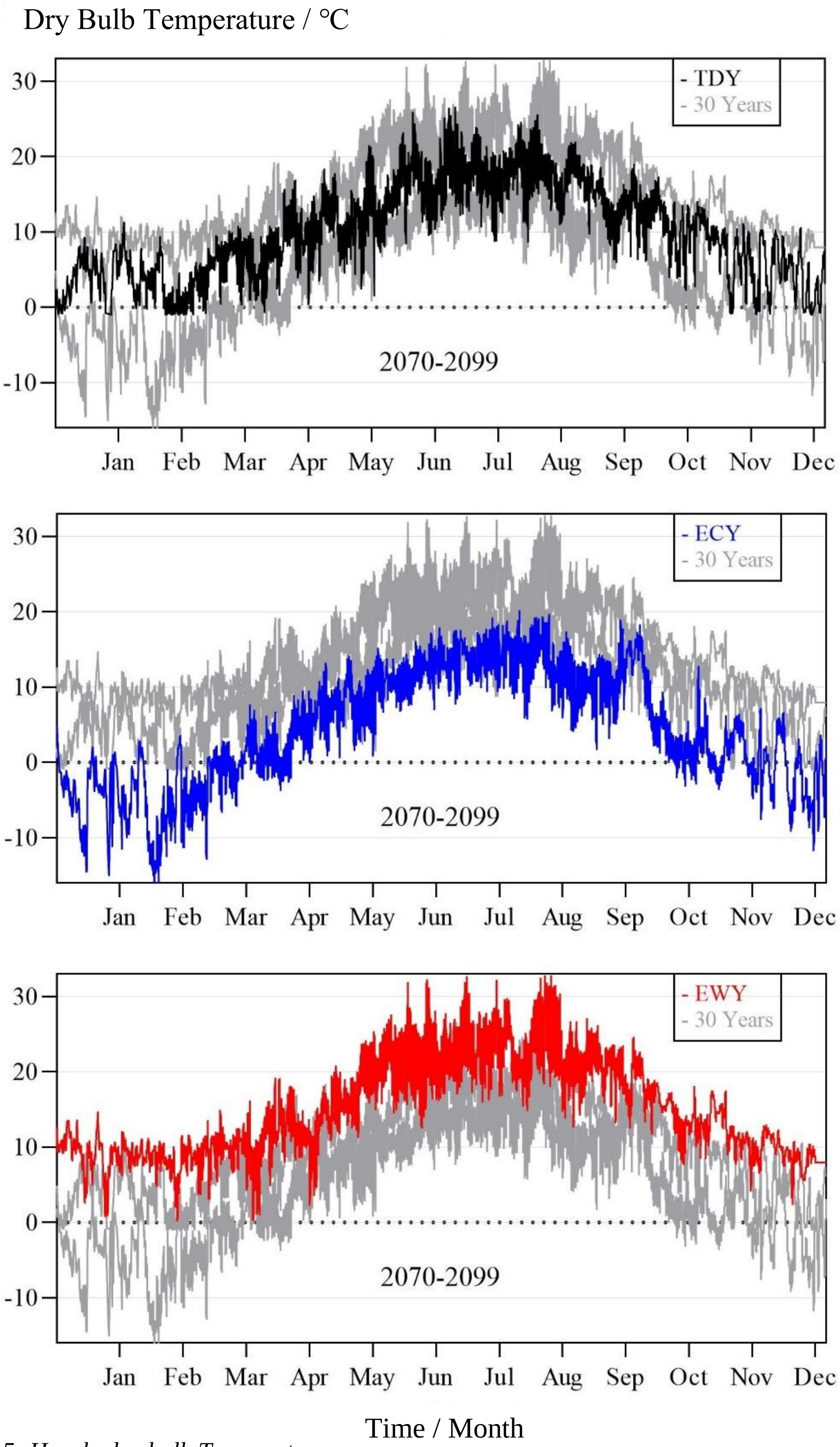

Figure 5: Hourly dry-bulb Temperature

Figure 6, illustrates the dry-bulb temperature for each climate data set. The minimum and maximum dry-bulb temperature for the current climate data have been shown by the black curve and they were -1.3 °C and 16.4 °C respectively. According to the other future climate data sets, the minimum dry-bulb temperature is 3.1 °C, 8.3 °C and -6.2 °C and the maximum dry-bulb temperature are 18 °C, 23.2 °C and 13.9 °C for TDY, EWY and ECY respectively.

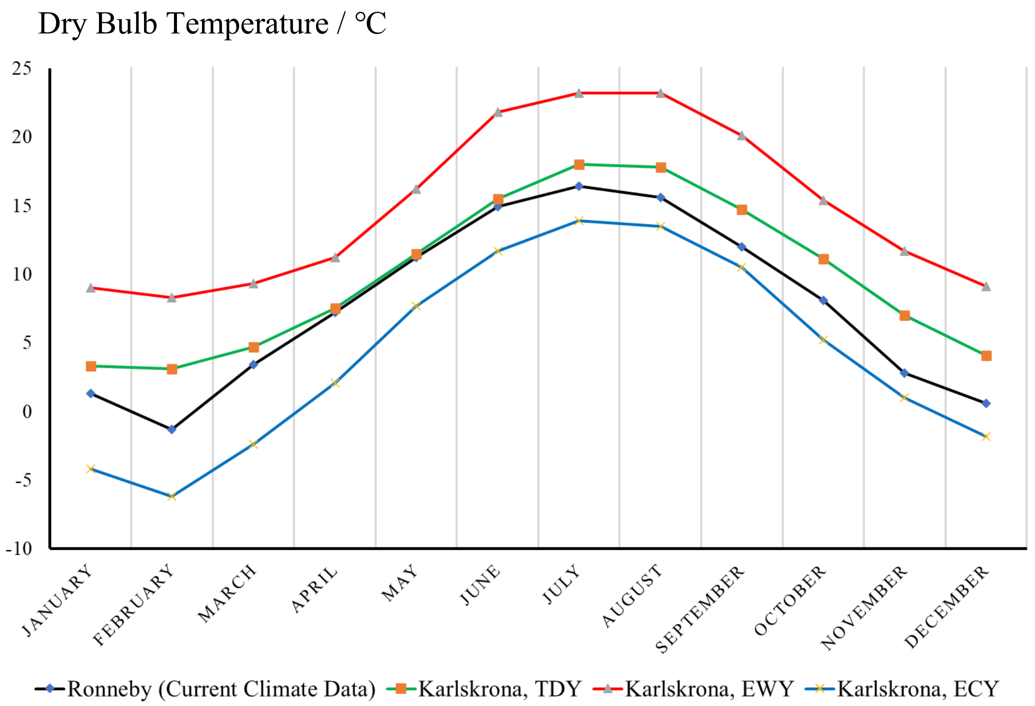

Figure 6: Dry-Bulb temperature of each climate data set

3 Results and Discussion

The results are discussed in this chapter and it is divided into 6 sections. It is started by the energy analysis results that comprise energy use and primary energy number. The results of the energy simulation by IDA ICE are illustrated in the energy use section as well as the calculation results based on BBR 26 are expressed in the primary energy number (EP_{pet}) part. The next section represents the results of the environmental impacts, including the results from OpenLCA. In section 3.3, the selected scenario (based on EP_{pet} and LCA) is optimized to provide more acceptable results in terms of EP_{pet}. The economic analysis results are represented in section 4 and after that section 5, expressed the best scenario in terms of integration EP_{pet}, LCA and LCC. In this section, the Single-Point Rate (SPR) calculation results are provided. Finally, the results of future climate analysis are shown in section 6.

3.1 Energy Analysis

3.1.1 Energy use

In this project, the thermal conductivity (λ-Value) of all proposed building envelope insulations had values very close to each other that were around 0.035 – 0.044 W/mK. Since, the annual domestic hot water demand and the annual property energy were constant for all scenarios as follows 10.15 kWh/m^2 per year and 14.81 kWh/m^2 per year respectively, therefore, the annual total energy use had a minor disparity. The scenarios which included bio-base insulation material such as wood fibre and cellulose have higher heating and cooling energy use compared to other scenarios because of their lower thermal conductivities. On the other hand, glass wool and mineral wool insulation materials acted more efficiently in the aspect of energy use due to their higher thermal conductance. Figures 7a , 7b and 8, show heating/cooling demand and the total annual energy use in the building per building conditioned area.

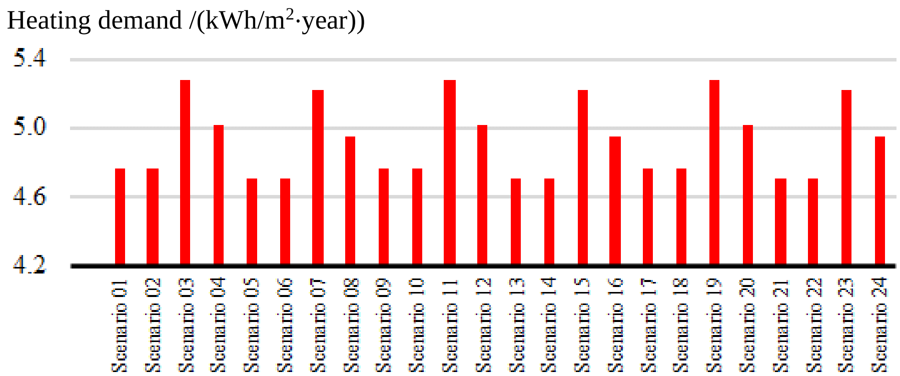

Figure 7a: Annual heating demand

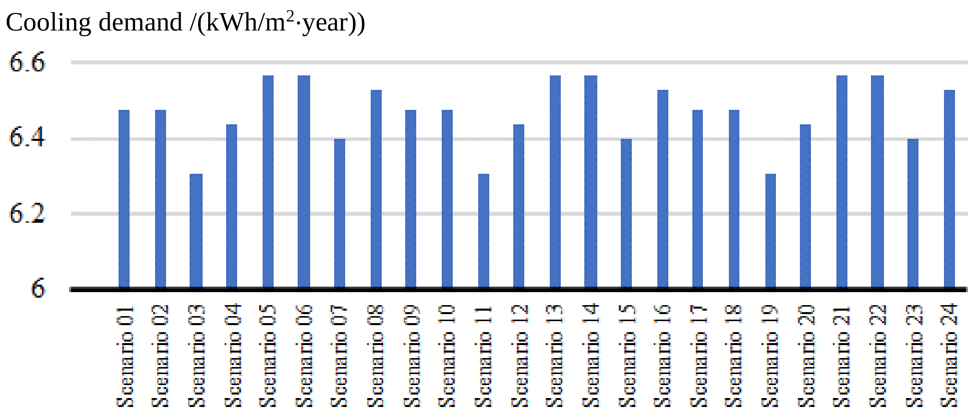

Figure 7b: Annual cooling demand

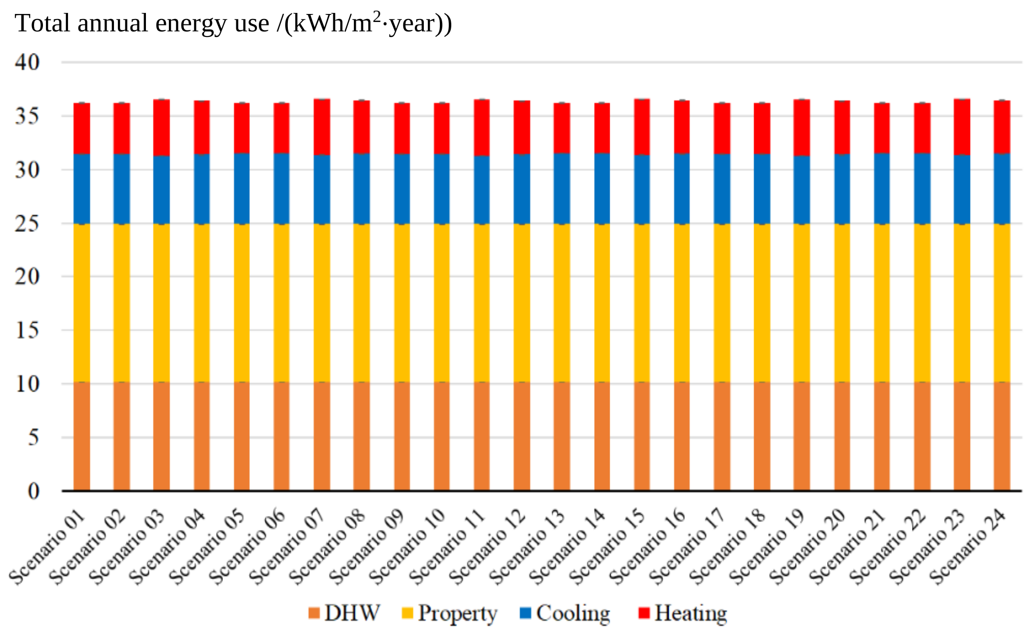

Figure 8: Annual energy use

The two different air duct systems, experienced differences in thermal conductivity and ducts surface area due to change the geometric shape. It was led to a minor change in heat gain and loss in heating and cooling energy use demand respectively for each scenario as shown in table 17.

Table 17: Heat gain and loss due to air duct alternatives

Duct Type	Annual heat gain / (kWh/ ($m^2 \cdot$ year))
Pre-insulated rectangular duct (PRD)	-1.17
Spiral duct + closed-cell elastomeric foam insulation (SPD)	-2.58

3.1.2 Primary energy number (EP_{pet})

Reference to BBR 26 the primary energy number was calculated according to the EP_{pet} equation. Figure 9, presents EP_{pet} for each scenario that complies with the standard requirement that is stated EP_{pet} that should not exceed 85 kWh/m^2_{Atemp}, annually for residential building. All the scenarios' EP_{pet} results achieved the standards with a considerable margin which is more than 50%. The building thus met the energy requirements a margin of 20 %, which is a respectable safety margin. The result had no safety margin included and it was therefore recommended to have a good margin on the favour of BBR requirements. According to figure 9, scenarios 5, 6, 13, 14, 21 and 22 achieved the lowest amount of primary energy number with the value of 48.31 kWh/m^2_{Atemp}. In these scenarios, the insulations with the lower u-value were employed for the external walls and roofs.

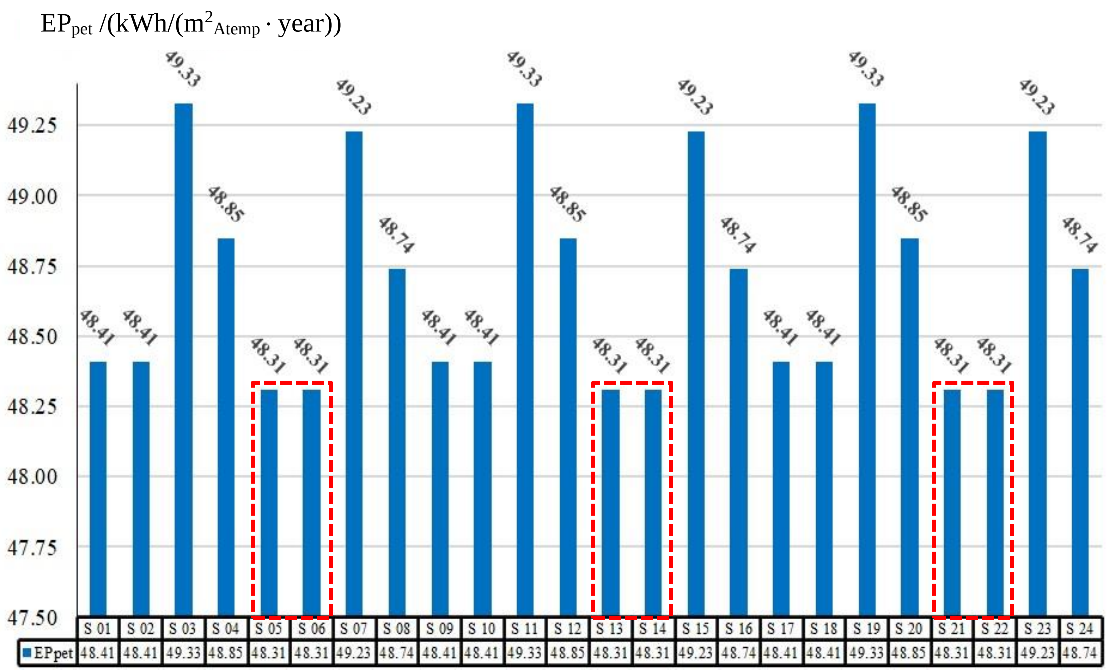

Figure 9: Primary energy number

3.2 Life Cycle Assessment (LCA)

Life cycle assessment was implemented according to QS for proposed construction materials shows in the bill of quantity (BOQ) at table 18.

Table 18: BOQ of proposed construction's materials

Building envelope thermal insulation Volume / m^3	**Spiral duct surface area / m^2**	**Spiral duct insulation volume / m^3**	**Pre-insulated rectangular duct surface area / m^2**	**Foundation concrete volume / m^3**
471	847	10	1019	63

3.2.1 Material Production Phase (A1-A3)

This study was concentrated on the global warming potential category impact (GWP) as the main concern, thus the CO_2 emission was focused. Figure 10, demonstrates the amount of CO_2 emission for each square meter of heated area (A_{temp}) in the production module (A1-A3).

The graph shows bio-based thermal insulation material wood fibre and cellulose have negative GWP values. It is basically because of the ability of storage of CO_2 in the organic wood structure while trees growing as claimed by Estokova and Porhincak [40]. However, glass wool performed better than mineral wool as inorganic insulation material since production energy use of glass wool was less comparing to mineral wool.

In the air Ducting system, spiral duct system with thermal insulation exceeded the double GWP value of rectangle pre-insulated duct that as a result of high energy use of hot rolled galvanized steel sheets production as a raw material of spiral duct. However, aluminium production energy use is extremely higher compared to steel production but the rectangular pre-insulated duct has a very small amount of aluminium foil in thickness (60E-3 mm) which presents around 0.6 % of the total product volume.

The ready-mix green concrete provided a lower GWP due to using the waste of concrete in the mixture design. In another word, to produce the green concrete the recycled concrete was employed to emit CO_2 at least 30% lower than the normal concrete. The Romanian concrete had a higher level of CO_2 emission compared to those.

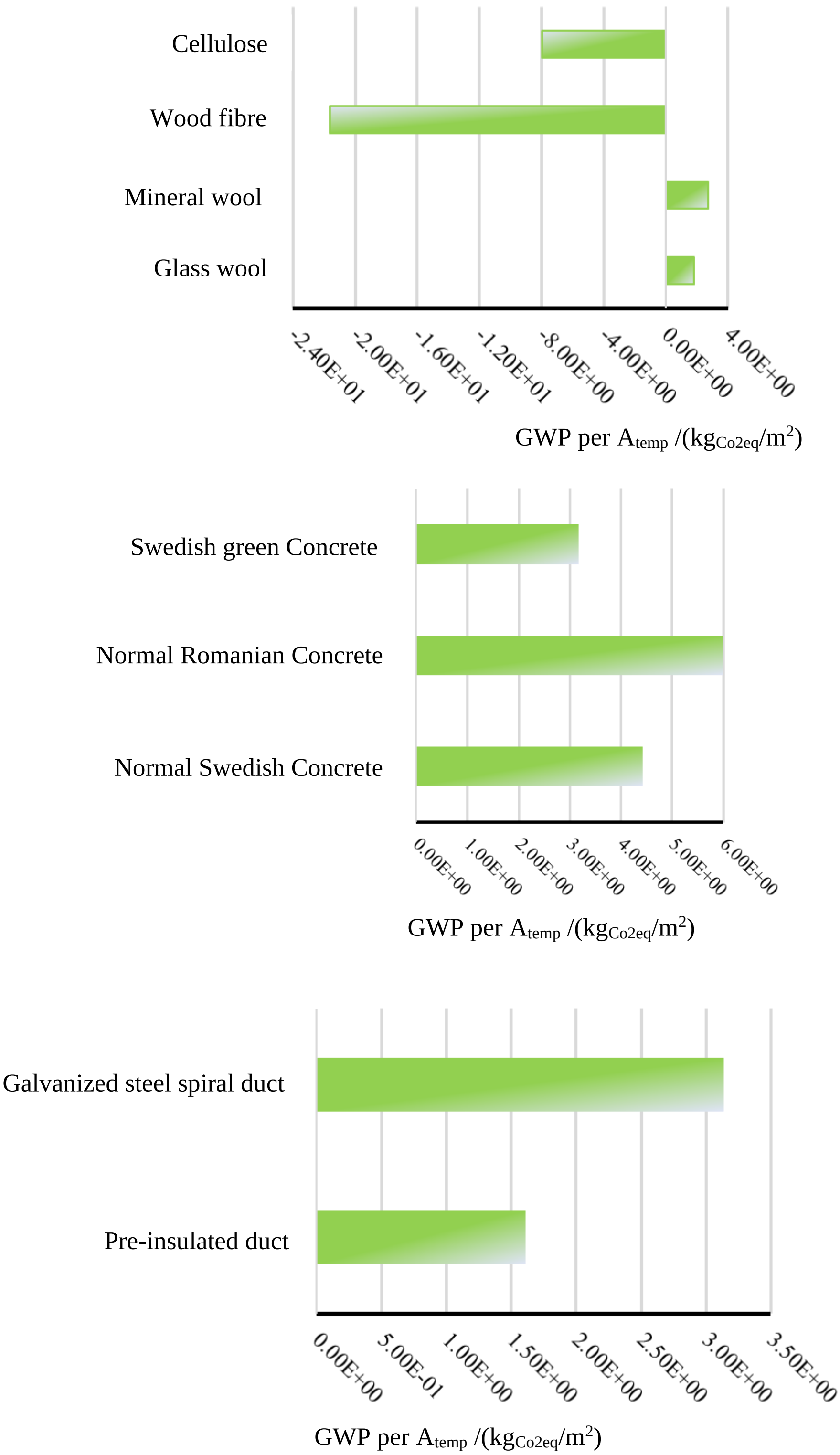

Figure 10: Global warming potential (GWP) impact category of proposed construction material in production phase (A1-A3)

3.2.2 Transportation Phase (A4)

Transportation phase assessment in LCA for each proposed material using OpenLCA is shown in Figures 11, In fact, the CO_2 emission related to the transportation phase is a function of mass and distance. Therefore, for insulation material wood fibre generates the highest amount of GWP due to high density of this insulation material and the far travelling distance.

The same concept was considered for air ducting material whilst rectangular pre-insulated duct is lighter than galvanized steel spiral duct, however, the spiral duct is manufactured locally and the pre-insulated duct is imported. In addition, all the concrete travel distances were considered the same for all suppliers but the variation of densities of concrete types have led to different values of GWP.

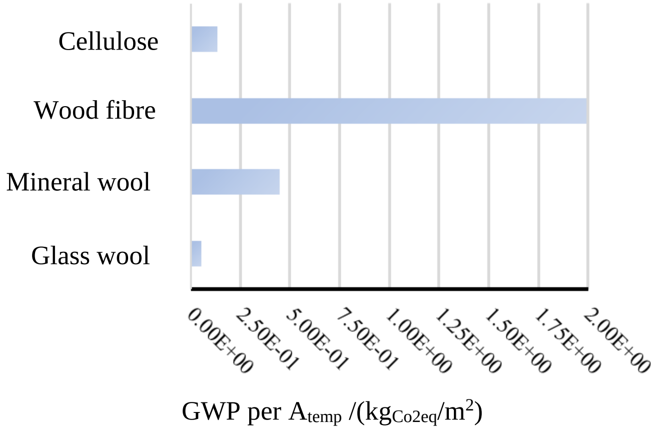

Figure 11a: Global warming potential (GWP) impact category of thermal insulations in Transportation phase (A4)

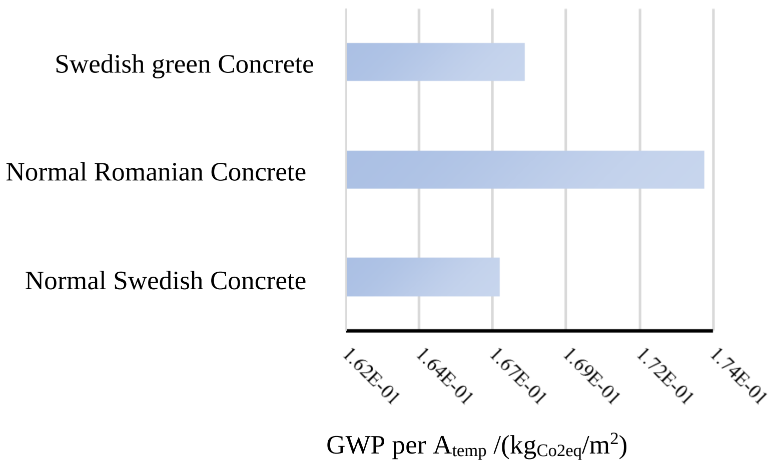

Figure 11b: Global warming potential (GWP) impact category of ready-mix concrete in Transportation phase (A4)

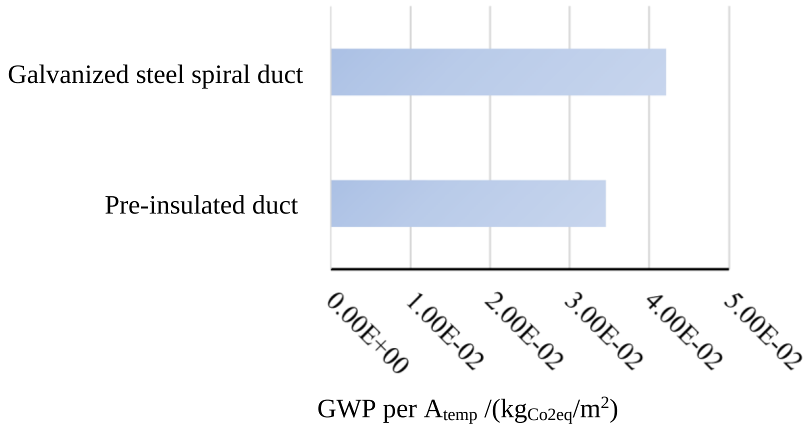

Figure 11c: Global warming potential (GWP) impact category of air ducting system in Transportation phase (A4)

3.2.3 Use Phase (B)

Global warming potential (GWP) impact category was assessed based on each proposed scenario according to their proposed building materials using OpenLCA software. Figure 12, presents the amount of CO_2 emission for each scenario whereas GWP is linked linearly with the building energy use for 50 years as the building life span.

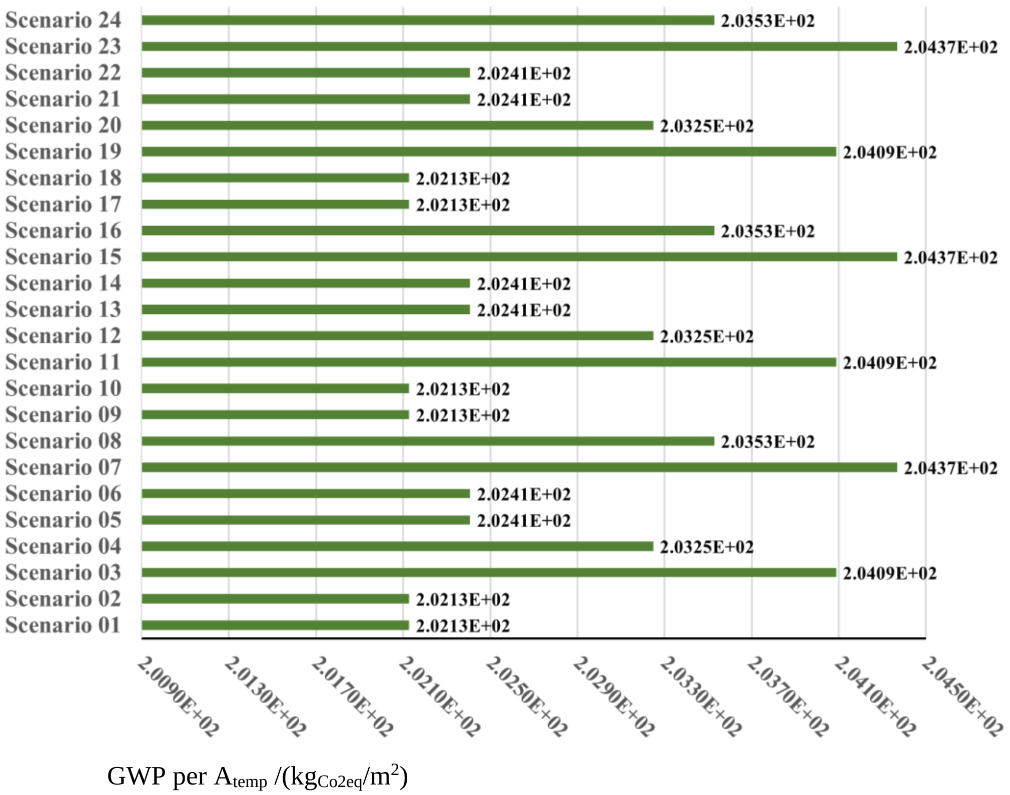

Figure 12: Global warming potential (GWP) impact category of proposed scenarios in Use phase (B)

Table 19, illustrates the aggregate values of GWP for each phase that shows the optimum scenario was scenario 19 by 1.089E+2 kg_{CO2eq}/m^2. It was mainly in the favour of negative CO_2 emission value of wood fibre and lower value of CO_2 emission of the rectangular pre-insulated duct system and green concrete.

Table 19: Total GWP for all proposed scenarios

Scenarios	**GWP Per A_{temp} / (kg_{CO2eq}/m^2)**			
	A1-A3 Production	**A4 Transportation**	**B Use**	**Total**
Scenario 01	7.84E+00	2.53E-01	2.02E+02	2.10E+02
Scenario 02	8.74E+00	6.51E-01	2.02E+02	2.12E+02
Scenario 03	-1.56E+01	2.19E+00	2.04E+02	1.91E+02
Scenario 04	-1.94E+00	3.35E-01	2.03E+02	2.02E+02
Scenario 05	9.37E+00	2.61E-01	2.02E+02	2.12E+02
Scenario 06	1.03E+01	6.59E-01	2.02E+02	2.13E+02
Scenario 07	-1.41E+01	2.20E+00	2.04E+02	1.93E+02
Scenario 08	-4.13E-01	3.43E-01	2.04E+02	2.03E+02
Scenario 09	9.42E+00	2.60E-01	2.02E+02	2.12E+02
Scenario 10	1.03E+01	6.58E-01	2.02E+02	2.13E+02
Scenario 11	-1.40E+01	2.20E+00	2.04E+02	1.92E+02
Scenario 12	-3.58E-01	3.42E-01	2.03E+02	2.03E+02
Scenario 13	1.10E+01	2.68E-01	2.02E+02	2.14E+02
Scenario 14	1.19E+01	6.65E-01	2.02E+02	2.15E+02
Scenario 15	-1.25E+01	2.20E+00	2.04E+02	1.94E+02
Scenario 16	1.17E+00	3.50E-01	2.04E+02	2.05E+02
Scenario 17	6.59E+00	2.54E-01	2.02E+02	2.09E+02
Scenario 18	7.49E+00	6.52E-01	2.02E+02	2.10E+02
Scenario 19	-1.68E+01	2.19E+00	2.04E+02	**1.89E+02**
Scenario 20	-3.19E+00	3.36E-01	2.03E+02	2.00E+02
Scenario 21	8.12E+00	2.62E-01	2.02E+02	2.11E+02
Scenario 22	9.02E+00	6.59E-01	2.02E+02	2.12E+02
Scenario 23	-1.53E+01	2.20E+00	2.04E+02	1.91E+02
Scenario 24	-1.66E+00	3.44E-01	2.04E+02	2.02E+02

3.3 Scenarios Optimization process

For further assessment, the results of GWP and EP_{pet} were drawn on a 2D graph for each scenario. The best scenario is the closest point to the zero-point coordinate due to lower GWP and lower EP_{pet} simultaneously. It was found that scenario 21 with co-ordinations 48.31 $EP_{pet}/(kWh/(year \cdot m^2))$ and 2.11E+02 $GWP/(kg_{CO2eq}/m^2)$ was the optimum option in both aspects as shown in figure 13.

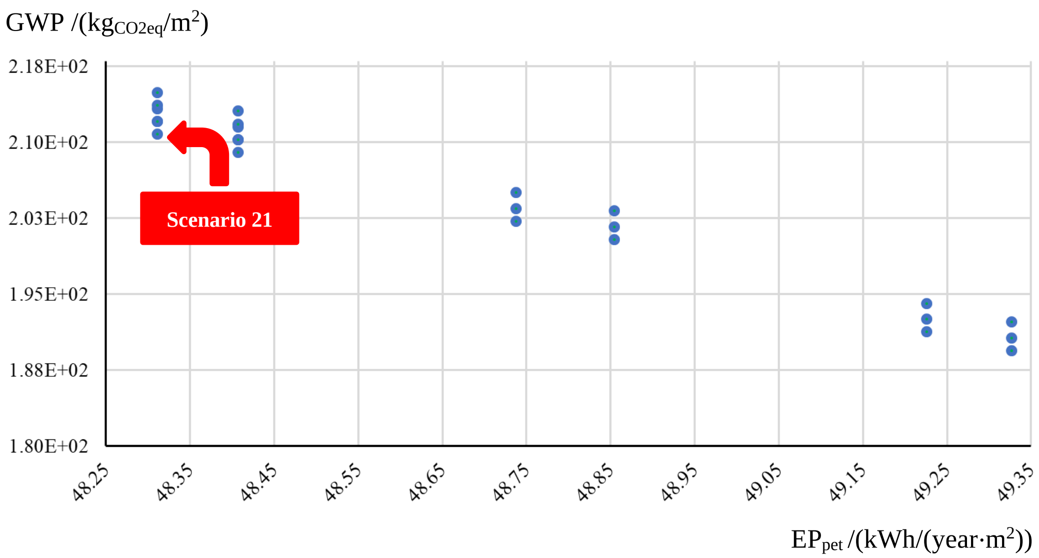

Figure 13: Integration of GWP and EP$_{pet}$ for all proposed scenarios

It was found that the wooden fibre scenarios had the lowest GWP impacts nevertheless they could not compete for building's energy use aspect because of the high value of their thermal conductivity. Therefore, the insulation thickness of the wood fibre was increased by 50 mm to be able to contest fossil based thermal insulation material respecting to the energy use of the building. Figure 14, shows the wooden fibre insulation thickness increasing effect on primary energy and Global warming potential value. In fact, it was led to the 23rd scenario that has co-ordination 48.28 EP$_{pet}$/(kWh/(year·m^2)) and 1.85E+02 GWP/(kg$_{CO2eq}$/m^2) was the nearest to the origin point and became the top-notch option on both aspects.

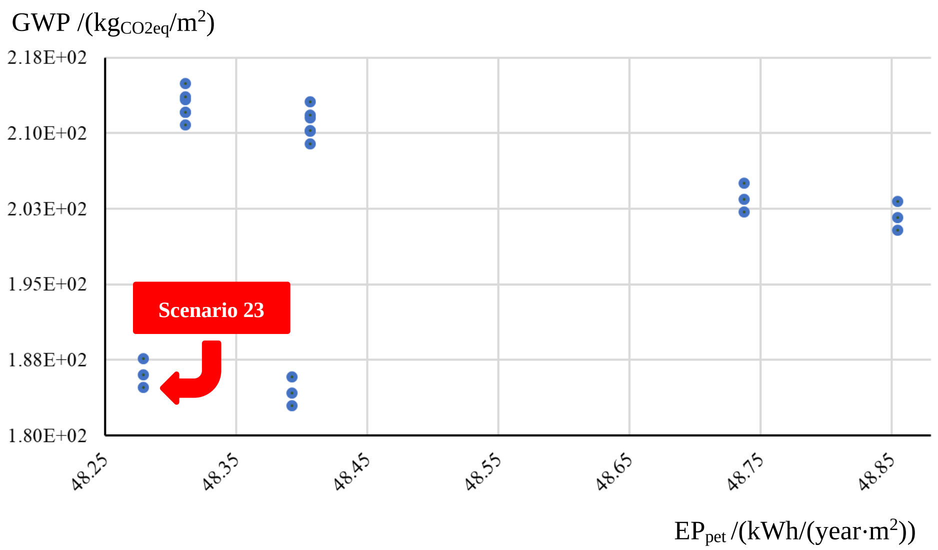

Figure 14: Integration of GWP and EP$_{pet}$ for all proposed scenarios after increasing the thickness of wood fibre by 50mm

3.4 Life cycle costing (LCC)

Life cycle costing analysis was conducted for all proposed scenarios included the improved scenarios as well to have thirty scenarios in total. The analysis was based on the Net Present Value (NPV) method which showed the lowest value of NPV at the ninth scenario with a total amount of 12.98 MSEK. The ninth scenario was comprised of glass wool insulation, rectangular pre-insulated air duct and Romanian concrete those materials had the lowest raw materials prices which led to this result. Whereas, other costs such as the energy used cost have slight disparities between alternatives. Figure 15, demonstrates the NPVs for the initial and running costs for all scenarios. Further detail numbers for each cost are presented in the appendix.

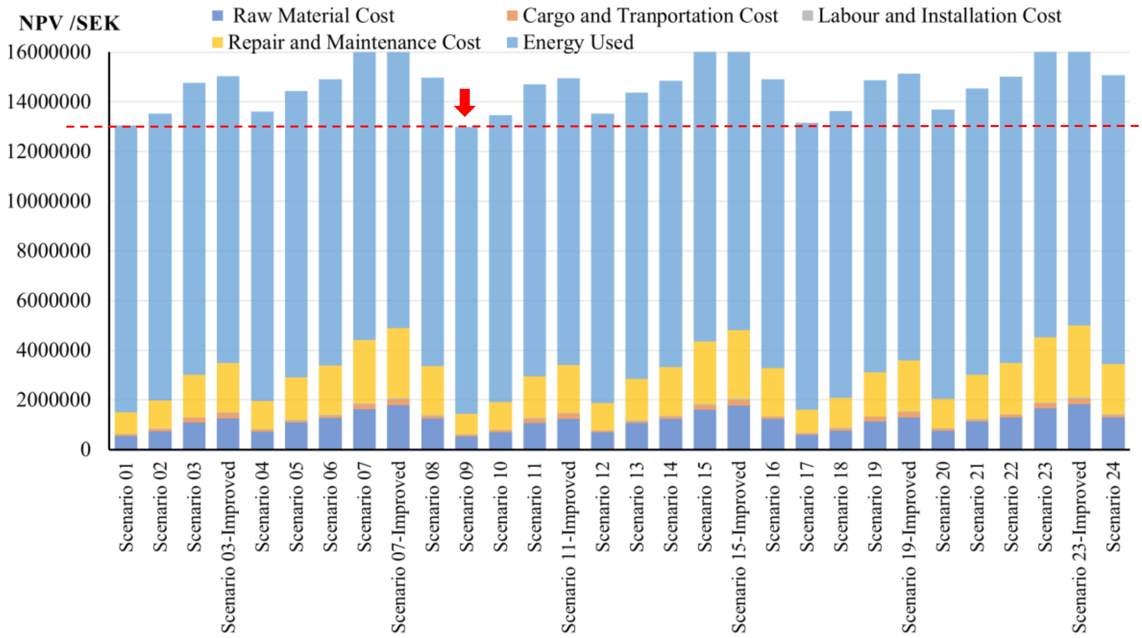

Figure 15: NPVs for the estimated costs for all proposed scenarios

3.5 Integration of Energy Analysis, LCA and LCC

Single-Point Rate (SPR) calculations were carried out to detect the optimum scenario according to proposed weighting system options in terms of these three aspects: EP_{pet}, LCA and LCC. Table 20, shows the minimum SPR values and its corresponding scenario.

Table 20: Minimum SPR values and corresponding scenarios number

Option	Weighting factors			Minimum SPR values	Related Scenario
	EP_{pet}	LCA	LCC		
Option 01	33 %	33 %	33 %	9.16E-01	Scenario – 19 Improved
Option 02	**40 %**	30 %	30 %	9.23E-01	Scenario – 19 Improved
Option 03	30 %	**40 %**	30 %	9.10E-01	Scenario – 19 Improved
Option 04	30 %	30 %	**40 %**	9.04E-01	Scenario – 01

The results in the table declare that improved scenario 19 that has the wooden fibre, rectangular pre-insulated duct and green concrete had the lowest SPR in options 1, 2 and 3 when LCC had the lowest/equal weighting factor. On the other hand, while LCC weighting factor had been considered as the highest impact that led to scenario 01 that consisted the insulation glass wool, rectangular pre-insulated duct and normal Swedish concrete. Actually, these components led to one of the lowest scenarios in the aspect of NPV.

3.6 Future Climate Analysis

The future climate analysis was assessed for three different weather data sets comprised of TDY, EWY and ECY. Figure 16, compares space heating energy demand based on current weather data and TDY. The top graphs are the hourly data and the bottom one is the monthly accumulative data for space heating energy demand. According to them, the space heating energy demands based on the current weather data and TDY are 47556 kWh/year and 26297 kWh/year respectively. In other words, the space heating energy demand for the current weather data is 45 % higher than TDY in the future. It might be due to global warming and higher outdoor temperature in the future. Therefore, the building needs to purchase a lower amount of heating energy in that time period in the future.

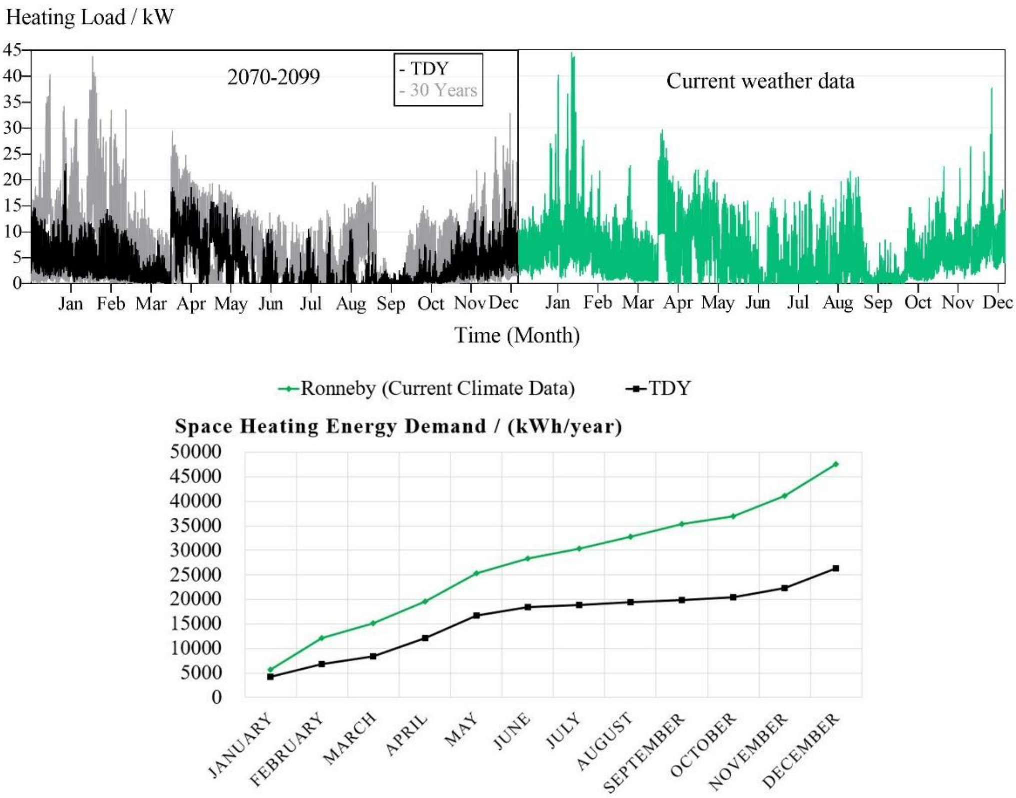

Figure 16: Space heating energy demand

According to figure 17, the cooling energy demand for the current weather data is 80471 kWh/year and based on TDY is 165122 kWh/year. In fact, in the next 50 years, this project almost needs twice amount of cooling energy to meet the thermal comfort set-points. Actually, due to global warming, the cooling demand will be higher in future and it could be the main reason to experience that.

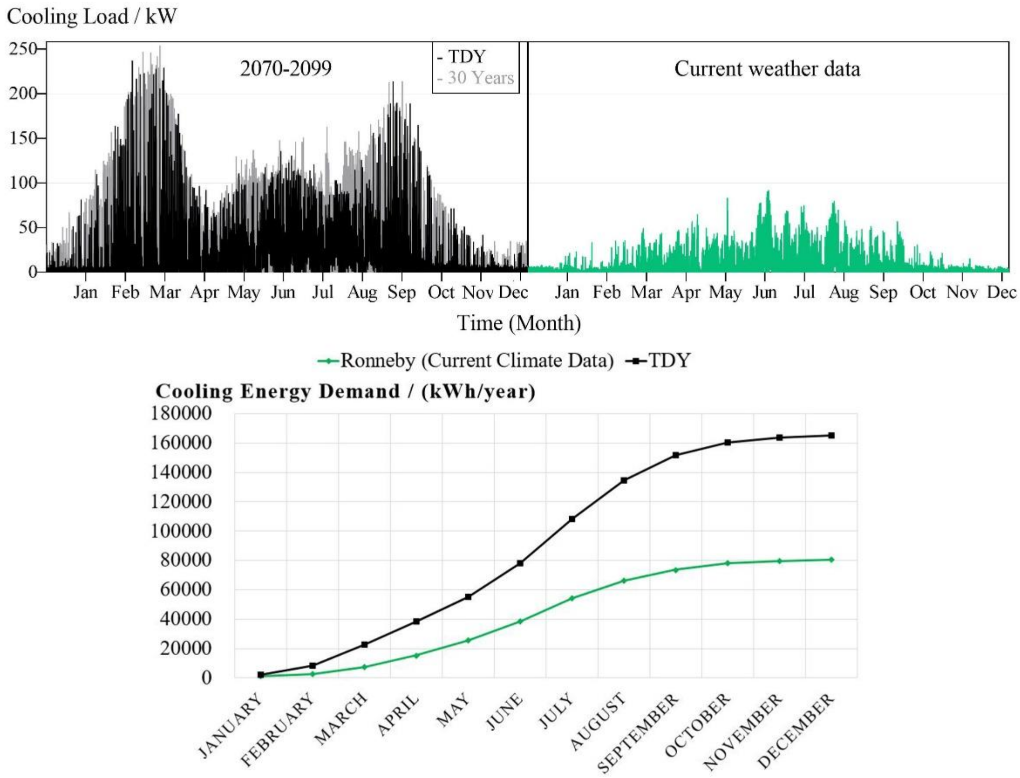

Figure 2: Cooling energy demand

Figure 18, shows the boxplot based on the hourly data of the space cooling load and cooling load as well. Based on that, the heating energy demand will be increased by 27 % for ECY condition compared to the current condition. Moreover, the cooling energy demand will be enhanced by 310 % with respect to EWY. This calculation could be useful for the client to consider a suitable infrastructure for the future to be able to cover this amount of energy and sizing the cooling and heating systems capacities. It is also worth mentioning that the EWY and ECY are the extreme weather data and the probability of occurring these conditions are very low.

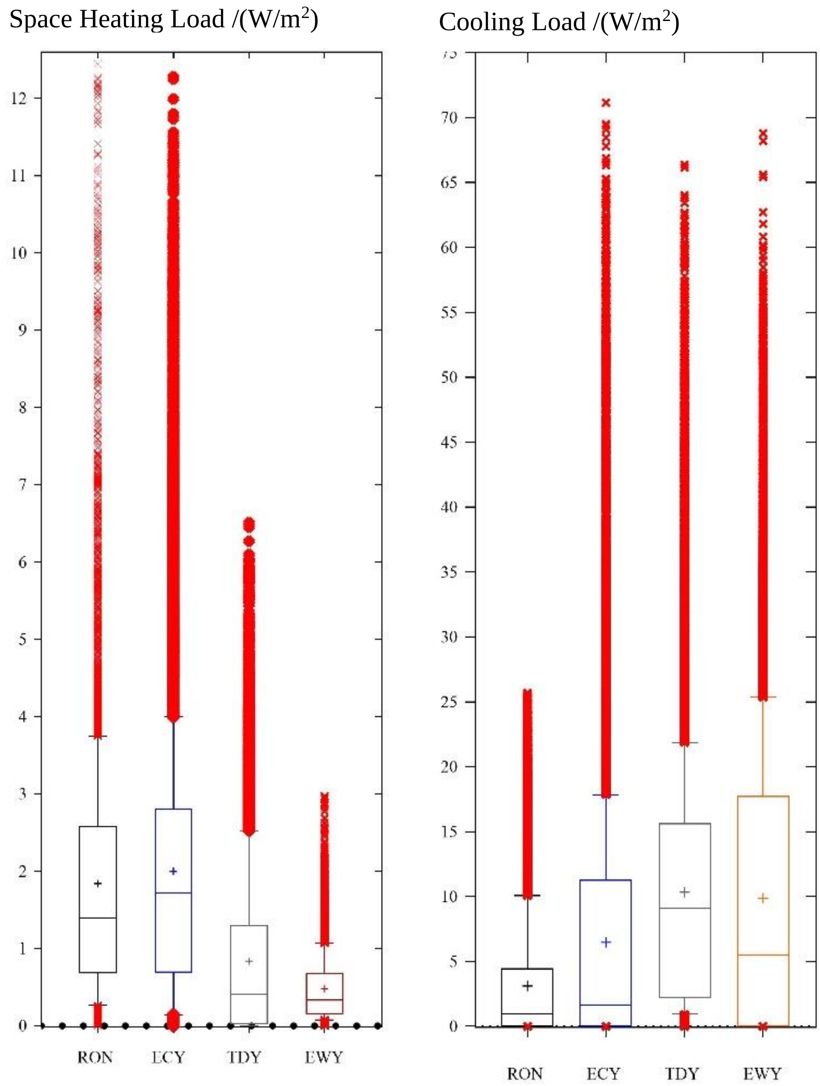

Figure 3: Hourly data of cooling energy demand and space heating demand based on different weather data, TDY, EWY, ECY

The CO_2 emissions based on the current weather data and the future weather data are illustrated in figure 19. Based on this figure, this building will provide 8.15×10^5 kg_{CO2eq}/50 year due to energy use during the building life span. It is almost 14% higher than the current CO_2 emission of the building. In fact, the current CO_2 emission is 7.22×10^5 kg_{CO2eq}/50 years. The main reason to have a higher CO_2 emission in the future is the energy use of the building will be increased considerably for the cooling demand.

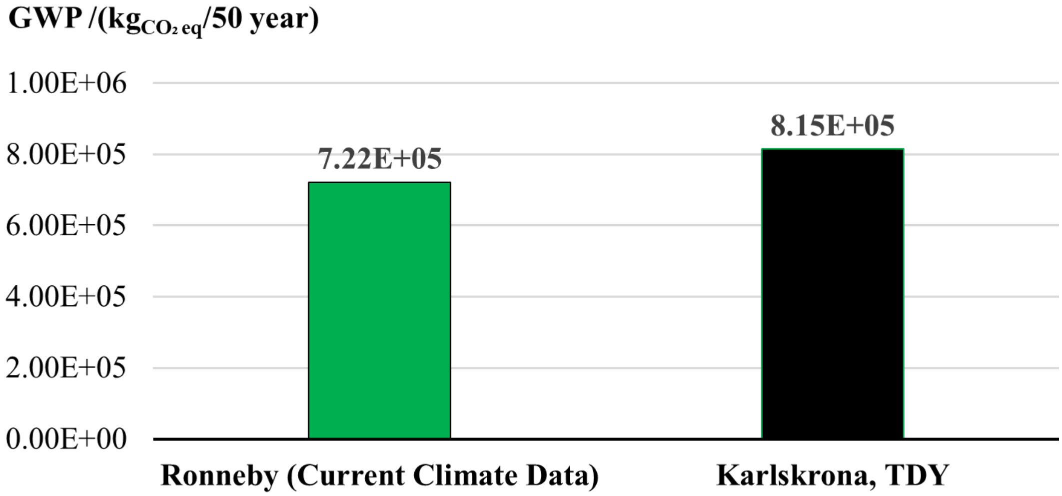

Figure 4: CO_2 emission based on current weather data and future weather data

4 Conclusion

This project was conducted to investigate about 3 construction materials in terms of energy performance, LCA and LCC. The first material was thermal insulation and to assessed that for the external walls and roofs, 2 bio-based materials were compared by 2 fossil-based materials. The second material was ready-mix concrete for the foundation. To assess that, 3 types of ready-mix concrete including 1 green concrete and 2 normal concretes were assessed. The third material was air duct for the HVAC system that 2 types of that including pre-insulated rectangular duct and galvanized steel spiral duct were investigated. Integration of these materials created 24 scenarios which one of them were determined as the optimum one in the favor of energy use, LCA and LCC. In the final step, the future climate analysis was conducted for the best scenario to demonstrate energy performance and environmental impact from 2070 to 2099.

As a conclusion, employing bio-based materials could be helpful to achieve the goal of having a sustainable building project. The wood fiber and cellulose were selected to investigate as the bio-based thermal insulation for the external walls and the roof. The CO_2 emission of both were negative values and it is mainly because they are produced by the wood. Basically, the tree absorbs the CO_2 from the air and if the constructors tend to use these types of insulation, it would provide the remarkable effects on the saving of CO_2 emission due to using the bio-based thermal insulation. Two other fossil-based insulations namely mineral wool and glass wool were compared to these bio-based insulations to show the difference of using them in terms of environmental impacts, primary energy use and economic feasibility. Actually, due to lower U-value of the glass wool and the mineral wool, they illustrated the better results in terms of primary energy use, however, with increasing the thickness of wood fiber it can be compensated. In addition, the price of wood fiber is higher compared to other insulations. However, if the environmental impacts are more important than economy issues (10% more), it is highly recommended to use the bio-based thermal insulation.

To investigate the ready-mix concrete, the foundation of the project was selected and three different types of insulation were checked. As a conclusion, using the green concrete was the best in terms of environmental impacts, while the price of that was almost 20% higher than the normal concrete. The main reason is using the waste material in the producing of the green concrete to save at least 30% of CO_2 emission in comparison with the normal concrete. The green concrete can also provide the same characteristics of the normal concrete in the favour of compressive strength, exposure class and water to cement ratio.

The pre-insulated rectangular duct not only demonstrated the lower environmental impacts but also, it had a lower price in comparison with the spiral duct system. Since the duct surface area in the rectangular shape is higher than the spiral shape the transmission heat loss is higher. It means that the pre-insulated rectangular duct experienced the higher primary energy use number, while it was not noticeable.

As the main conclusion, the scenario which was included the bio-based materials was selected as the best scenario in terms of integration of environmental impact, primary energy and economy. In that scenario the wood fiber was selected as the thermal insulation, the green concrete was determined as the ready-mix concrete and the pre-insulated rectangular duct system was chosen the air duct system. It is also worth mentioning that, the lower energy use does not mean the sustainable one. This study strongly illustrated that to find the sustainable building design the life cycle assessment needs to be performed in addition to the energy analysis.

Moreover, to ensure the building has a future climate resilience in terms of energy-efficient and environmental impacts, the analysis regarding the future climate was performed based on three climate data sets for the time period between 2070 and 2099. The final selected scenario which comprises the bio-based materials illustrated that the building can cover the heating demand in the intended time period while regarding the supporting cooling demand the more suitable infrastructure is expected to cover the higher cooling load (almost 2 times more) in the future. Furthermore, it is optimistically expected to have lower CO_2 emission than the achieved results for the selected scenario in this study according to the global direction of greener energy generation.

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6 Appendix

6.1 Values of Global Warming Potential (GWP)

LCA				Prodction Material	Transportation	Energy Use	Total
Scenario	Insulation	Duct Type	Concrete Type	GWP Per Atemp kg CO_2 eq./m^2 A1-A3	GWP Per Atemp kg CO_2 eq./m^2 A4	GWP Per Atemp kg CO_2 eq./m^2 B - USE	GWP Per Atemp kg CO_2 eq./m^2 A1-A5 & B
Scenario 01	Glass wool	Preinsulated Duct	Swedish Concrete	7.84E+00	2.53E-01	2.02E+02	2.10E+02
Scenario 02	Mineral Wool	Preinsulated Duct	Swedish Concrete	8.74E+00	6.51E-01	2.02E+02	2.12E+02
Scenario 03-Improved	Wood Fibre 25 cm	Preinsulated Duct	Swedish Concrete	-2.02E+01	2.62E+00	2.02E+02	1.84E+02
Scenario 04	Cellulose	Preinsulated Duct	Swedish Concrete	-1.94E+00	3.35E-01	2.03E+02	2.02E+02
Scenario 05	Glass wool	Spiral Duct	Swedish Concrete	9.37E+00	2.61E-01	2.02E+02	2.12E+02
Scenario 06	Mineral Wool	Spiral Duct	Swedish Concrete	1.03E+01	6.59E-01	2.02E+02	2.13E+02
Scenario 07-Improved	Wood Fibre 25 cm	Spiral Duct	Swedish Concrete	-1.87E+01	2.63E+00	2.02E+02	1.86E+02
Scenario 08	Cellulose	Spiral Duct	Swedish Concrete	-4.13E-01	3.43E-01	2.04E+02	2.03E+02
Scenario 09	Glass wool	Preinsulated Duct	Romanian Concrete	9.42E+00	2.60E-01	2.02E+02	2.12E+02
Scenario 10	Mineral Wool	Preinsulated Duct	Romanian Concrete	1.03E+01	6.58E-01	2.02E+02	2.13E+02
Scenario 11-Improved	Wood Fibre 25 cm	Preinsulated Duct	Romanian Concrete	-1.87E+01	2.62E+00	2.02E+02	1.86E+02
Scenario 12	Cellulose	Preinsulated Duct	Romanian Concrete	-3.58E-01	3.42E-01	2.03E+02	2.03E+02
Scenario 13	Glass wool	Spiral Duct	Romanian Concrete	1.10E+01	2.68E-01	2.02E+02	2.14E+02
Scenario 14	Mineral Wool	Spiral Duct	Romanian Concrete	1.19E+01	6.65E-01	2.02E+02	2.15E+02
Scenario 15-Improved	Wood Fibre 25 cm	Spiral Duct	Romanian Concrete	-1.71E+01	2.63E+00	2.02E+02	1.88E+02
Scenario 16	Cellulose	Spiral Duct	Romanian Concrete	1.17E+00	3.50E-01	2.04E+02	2.05E+02
Scenario 17	Glass wool	Preinsulated Duct	Green Concrete-Skanska	6.59E+00	2.54E-01	2.02E+02	2.09E+02
Scenario 18	Mineral Wool	Preinsulated Duct	Green Concrete-Skanska	7.49E+00	6.52E-01	2.02E+02	2.10E+02
Scenario 19-Improved	Wood Fibre 25 cm	Preinsulated Duct	Green Concrete-Skanska	-2.15E+01	2.62E+00	2.02E+02	1.83E+02
Scenario 20	Cellulose	Preinsulated Duct	Green Concrete-Skanska	-3.19E+00	3.36E-01	2.03E+02	2.00E+02
Scenario 21	Glass wool	Spiral Duct	Green Concrete-Skanska	8.12E+00	2.62E-01	2.02E+02	2.11E+02
Scenario 22	Mineral Wool	Spiral Duct	Green Concrete-Skanska	9.02E+00	6.59E-01	2.02E+02	2.12E+02
Scenario 23-Improved	Wood Fibre 25 cm	Spiral Duct	Green Concrete-Skanska	-2.00E+01	2.63E+00	2.02E+02	1.85E+02
Scenario 24	Cellulose	Spiral Duct	Green Concrete-Skanska	-1.66E+00	3.44E-01	2.04E+02	2.02E+02

Figure 5: Calculated values of Global Warming Potential (GWP) for each scenario

6.2 Values of Life Cycle Costing (LCC)

NPV for Proposed Scenrios				Intial Costs			Running Costs		Total Costs
Scenario	Insulation	Duct Type	Concrete Type	Raw Material Cost	Cargo and Tranportation Cost	Labour and Installation Cost	Repair and Maintenance Cost	Energy Used	Total of NPV
				SEK	SEK	SEK	SEK	SEK	SEK
Scenario 01	Glass wool	Preinsulated Duct	Swedish Concrete	552,367	67,258	16,571	870,263	11,548,591	13,055,050
Scenario 02	Mineral Wool	Preinsulated Duct	Swedish Concrete	727,540	84,948	21,826	1,146,251	11,548,591	13,529,156
Scenario 03	Wood Fibre 20 cm	Preinsulated Duct	Swedish Concrete	1,086,832	183,737	32,605	1,712,322	11,749,732	14,765,228
Scenario 03-Improved	Wood Fibre 25 cm	Preinsulated Duct	Swedish Concrete	1,257,600	209,274	37,728	1,981,369	11,545,523	15,031,494
Scenario 04	Cellulose	Preinsulated Duct	Swedish Concrete	721,418	72,940	21,643	1,136,606	11,646,365	13,598,971
Scenario 05	Glass wool	Spiral Duct Steel	Swedish Concrete	1,091,242	67,709	32,737	1,719,269	11,528,027	14,438,983
Scenario 06	Mineral Wool	Spiral Duct Steel	Swedish Concrete	1,266,414	85,400	37,992	1,995,256	11,528,027	14,913,089
Scenario 07	Wood Fibre 20 cm	Spiral Duct Steel	Swedish Concrete	1,625,707	184,188	48,771	2,561,328	11,727,963	16,147,957
Scenario 07-Improved	Wood Fibre 25 cm	Spiral Duct Steel	Swedish Concrete	1,796,475	209,726	53,894	2,830,375	11,527,082	16,417,551
Scenario 08	Cellulose	Spiral Duct Steel	Swedish Concrete	1,260,293	73,391	37,809	1,985,612	11,620,727	14,977,831
Scenario 09	Glass wool	Preinsulated Duct	Romanian Concrete	523,947	67,258	15,718	825,486	11,548,591	12,981,000
Scenario 10	Mineral Wool	Preinsulated Duct	Romanian Concrete	699,119	84,948	20,974	1,101,474	11,548,591	13,455,106
Scenario 11	Wood Fibre 20 cm	Preinsulated Duct	Romanian Concrete	1,058,412	183,737	31,752	1,667,545	11,749,732	14,691,178
Scenario 11-Improved	Wood Fibre 25 cm	Preinsulated Duct	Romanian Concrete	1,229,180	209,274	36,875	1,936,592	11,545,523	14,957,444
Scenario 12	Cellulose	Preinsulated Duct	Romanian Concrete	692,998	72,940	20,790	1,091,829	11,646,365	13,524,921
Scenario 13	Glass wool	Spiral Duct Steel	Romanian Concrete	1,062,821	67,709	31,885	1,674,492	11,528,027	14,364,934
Scenario 14	Mineral Wool	Spiral Duct Steel	Romanian Concrete	1,237,994	85,400	37,140	1,950,480	11,528,027	14,839,040
Scenario 15	Wood Fibre 20 cm	Spiral Duct Steel	Romanian Concrete	1,597,287	184,188	47,919	2,516,551	11,727,963	16,073,908
Scenario 15-Improved	Wood Fibre 25 cm	Spiral Duct Steel	Romanian Concrete	1,768,054	209,726	53,042	2,785,598	11,527,082	16,343,502
Scenario 16	Cellulose	Spiral Duct Steel	Romanian Concrete	1,231,872	73,391	36,956	1,940,835	11,620,727	14,903,782
Scenario 17	Glass wool	Preinsulated Duct	Green Concrete-Skanska	588,710	67,258	17,661	927,522	11,548,591	13,149,741
Scenario 18	Mineral Wool	Preinsulated Duct	Green Concrete-Skanska	763,883	84,948	22,916	1,203,509	11,548,591	13,623,848
Scenario 19	Wood Fibre 20 cm	Preinsulated Duct	Green Concrete-Skanska	1,123,175	183,737	33,695	1,769,581	11,749,732	14,859,920
Scenario 19-Improved	Wood Fibre 25 cm	Preinsulated Duct	Green Concrete-Skanska	1,293,943	209,274	38,818	2,038,627	11,545,523	15,126,185
Scenario 20	Cellulose	Preinsulated Duct	Green Concrete-Skanska	757,761	72,940	22,733	1,193,864	11,646,365	13,693,663
Scenario 21	Glass wool	Spiral Duct Steel	Green Concrete-Skanska	1,127,584	67,709	33,828	1,776,527	11,528,027	14,533,675
Scenario 22	Mineral Wool	Spiral Duct Steel	Green Concrete-Skanska	1,302,757	85,400	39,083	2,052,515	11,528,027	15,007,781
Scenario 23	Wood Fibre 20 cm	Spiral Duct Steel	Green Concrete-Skanska	1,662,050	184,188	49,861	2,618,586	11,727,963	16,242,649
Scenario 23-Improved	Wood Fibre 25 cm	Spiral Duct Steel	Green Concrete-Skanska	1,832,817	209,726	54,985	2,887,633	11,527,082	16,512,243
Scenario 24	Cellulose	Spiral Duct Steel	Green Concrete-Skanska	1,296,636	73,391	38,899	2,042,870	11,620,727	15,072,523

Figure 6: Calculated values of Life Cycle Costing (LCC) for each scenario

6.3 Values of integration of EP_{pet}, LCA and LCC

Scenario	Insulation	Duct Type	Concrete Type	Primary Energy EPpet kWh/m² year	LCA GWP Per A_{temp} A1-A5 & B kg CO_2 eq./m	LCC Total NPV SEK / m2	SPR [-]
Scenario 01	Glass wool	Preinsulated Duct	Swedish Concrete	48.41	2.10E+02	3,655	0.9165884
Scenario 02	Mineral Wool	Preinsulated Duct	Swedish Concrete	48.41	2.12E+02	3,788	0.9281812
Scenario 03	Wood Fibre 20 cm	Preinsulated Duct	Swedish Concrete	49.33	1.91E+02	4,134	0.9270385
Scenario 03-Improved	Wood Fibre 25 cm	Preinsulated Duct	Swedish Concrete	48.39	1.84E+02	4,208	0.9160821
Scenario 04	Cellulose	Preinsulated Duct	Swedish Concrete	48.85	2.02E+02	3,807	0.9172871
Scenario 05	Glass wool	Spiral Duct Steel	Swedish Concrete	48.31	2.12E+02	4,042	0.9466955
Scenario 06	Mineral Wool	Spiral Duct Steel	Swedish Concrete	48.31	2.13E+02	4,175	0.9582883
Scenario 07	Wood Fibre 20 cm	Spiral Duct Steel	Swedish Concrete	49.23	1.93E+02	4,521	0.9570841
Scenario 07-Improved	Wood Fibre 25 cm	Spiral Duct Steel	Swedish Concrete	48.28	1.86E+02	4,596	0.9461098
Scenario 08	Cellulose	Spiral Duct Steel	Swedish Concrete	48.74	2.03E+02	4,193	0.9471491
Scenario 09	Glass wool	Preinsulated Duct	Romanian Concrete	48.41	2.12E+02	3,634	0.9175626
Scenario 10	Mineral Wool	Preinsulated Duct	Romanian Concrete	48.41	2.13E+02	3,767	0.9291553
Scenario 11	Wood Fibre 20 cm	Preinsulated Duct	Romanian Concrete	49.33	1.92E+02	4,113	0.9280127
Scenario 11-Improved	Wood Fibre 25 cm	Preinsulated Duct	Romanian Concrete	48.39	1.86E+02	4,187	0.9170563
Scenario 12	Cellulose	Preinsulated Duct	Romanian Concrete	48.85	2.03E+02	3,786	0.9182612
Scenario 13	Glass wool	Spiral Duct Steel	Romanian Concrete	48.31	2.14E+02	4,022	0.9476697
Scenario 14	Mineral Wool	Spiral Duct Steel	Romanian Concrete	48.31	2.15E+02	4,154	0.9592625
Scenario 15	Wood Fibre 20 cm	Spiral Duct Steel	Romanian Concrete	49.23	1.94E+02	4,500	0.9580583
Scenario 15-Improved	Wood Fibre 25 cm	Spiral Duct Steel	Romanian Concrete	48.28	1.88E+02	4,575	0.9470840
Scenario 16	Cellulose	Spiral Duct Steel	Romanian Concrete	48.74	2.05E+02	4,172	0.9481232
Scenario 17	Glass wool	Preinsulated Duct	Green Concrete-Skanska	48.41	2.09E+02	3,681	0.9165630
Scenario 18	Mineral Wool	Preinsulated Duct	Green Concrete-Skanska	48.41	2.10E+02	3,814	0.9281557
Scenario 19	Wood Fibre 20 cm	Preinsulated Duct	Green Concrete-Skanska	49.33	1.89E+02	4,160	0.9270131
Scenario 19-Improved	Wood Fibre 25 cm	Preinsulated Duct	Green Concrete-Skanska	48.39	1.83E+02	4,235	0.9160567
Scenario 20	Cellulose	Preinsulated Duct	Green Concrete-Skanska	48.85	2.00E+02	3,834	0.9172617
Scenario 21	Glass wool	Spiral Duct Steel	Green Concrete-Skanska	48.31	2.11E+02	4,069	0.9466701
Scenario 22	Mineral Wool	Spiral Duct Steel	Green Concrete-Skanska	48.31	2.12E+02	4,202	0.9582629
Scenario 23	Wood Fibre 20 cm	Spiral Duct Steel	Green Concrete-Skanska	49.23	1.91E+02	4,547	0.9570587
Scenario 23-Improved	Wood Fibre 25 cm	Spiral Duct Steel	Green Concrete-Skanska	48.28	1.85E+02	4,623	0.9460844
Scenario 24	Cellulose	Spiral Duct Steel	Green Concrete-Skanska	48.74	2.02E+02	4,220	0.9471236

Figure 7: Calculated values of SPR for each scenario, EP_{pet} (33.33%), LCA (33.33%), LCC (33.33%)

Scenario	Insulation	Duct Type	Concrete Type	Primary Energy EPpet kWh/m² yea	LCA GWP Per A1-A5 & B kg CO_2	LCC Total NPV SEK / m2	SPR [-]
Scenario 01	Glass wool	Preinsulated Duct	Swedish Concrete	48.41	2.10E+02	3,655	0.9231462
Scenario 02	Mineral Wool	Preinsulated Duct	Swedish Concrete	48.41	2.12E+02	3,788	0.9335807
Scenario 03	Wood Fibre 20 cm	Preinsulated Duct	Swedish Concrete	49.33	1.91E+02	4,134	0.9344181
Scenario 03-Improved	Wood Fibre 25 cm	Preinsulated Duct	Swedish Concrete	48.39	1.84E+02	4,208	0.9226620
Scenario 04	Cellulose	Preinsulated Duct	Swedish Concrete	48.85	2.02E+02	3,807	0.9246820
Scenario 05	Glass wool	Spiral Duct Steel	Swedish Concrete	48.31	2.12E+02	4,042	0.9500518
Scenario 06	Mineral Wool	Spiral Duct Steel	Swedish Concrete	48.31	2.13E+02	4,175	0.9604863
Scenario 07	Wood Fibre 20 cm	Spiral Duct Steel	Swedish Concrete	49.23	1.93E+02	4,521	0.9612572
Scenario 07-Improved	Wood Fibre 25 cm	Spiral Duct Steel	Swedish Concrete	48.28	1.86E+02	4,596	0.9494594
Scenario 08	Cellulose	Spiral Duct Steel	Swedish Concrete	48.74	2.03E+02	4,193	0.9513242
Scenario 09	Glass wool	Preinsulated Duct	Romanian Concrete	48.41	2.12E+02	3,634	0.9240230
Scenario 10	Mineral Wool	Preinsulated Duct	Romanian Concrete	48.41	2.13E+02	3,767	0.9344576
Scenario 11	Wood Fibre 20 cm	Preinsulated Duct	Romanian Concrete	49.33	1.92E+02	4,113	0.9352950
Scenario 11-Improved	Wood Fibre 25 cm	Preinsulated Duct	Romanian Concrete	48.39	1.86E+02	4,187	0.9235388
Scenario 12	Cellulose	Preinsulated Duct	Romanian Concrete	48.85	2.03E+02	3,786	0.9255589
Scenario 13	Glass wool	Spiral Duct Steel	Romanian Concrete	48.31	2.14E+02	4,022	0.9509286
Scenario 14	Mineral Wool	Spiral Duct Steel	Romanian Concrete	48.31	2.15E+02	4,154	0.9613632
Scenario 15	Wood Fibre 20 cm	Spiral Duct Steel	Romanian Concrete	49.23	1.94E+02	4,500	0.9621340
Scenario 15-Improved	Wood Fibre 25 cm	Spiral Duct Steel	Romanian Concrete	48.28	1.88E+02	4,575	0.9503363
Scenario 16	Cellulose	Spiral Duct Steel	Romanian Concrete	48.74	2.05E+02	4,172	0.9522010
Scenario 17	Glass wool	Preinsulated Duct	Green Concrete-Skanska	48.41	2.09E+02	3,681	0.9231233
Scenario 18	Mineral Wool	Preinsulated Duct	Green Concrete-Skanska	48.41	2.10E+02	3,814	0.9335578
Scenario 19	Wood Fibre 20 cm	Preinsulated Duct	Green Concrete-Skanska	49.33	1.89E+02	4,160	0.9343952
Scenario 19-Improved	Wood Fibre 25 cm	Preinsulated Duct	Green Concrete-Skanska	48.39	1.83E+02	4,235	0.9226391
Scenario 20	Cellulose	Preinsulated Duct	Green Concrete-Skanska	48.85	2.00E+02	3,834	0.9246592
Scenario 21	Glass wool	Spiral Duct Steel	Green Concrete-Skanska	48.31	2.11E+02	4,069	0.9500289
Scenario 22	Mineral Wool	Spiral Duct Steel	Green Concrete-Skanska	48.31	2.12E+02	4,202	0.9604635
Scenario 23	Wood Fibre 20 cm	Spiral Duct Steel	Green Concrete-Skanska	49.23	1.91E+02	4,547	0.9612343
Scenario 23-Improved	Wood Fibre 25 cm	Spiral Duct Steel	Green Concrete-Skanska	48.28	1.85E+02	4,623	0.9494365
Scenario 24	Cellulose	Spiral Duct Steel	Green Concrete-Skanska	48.74	2.02E+02	4,220	0.9513013

Figure 8: Calculated values of SPR for each scenario, EP_{pet} (40%), LCA (30%), LCC (30%)

Scenario	Insulation	Duct Type	Concrete Type	Primary Energy EPpet kWh/m² yea	LCA GWP Per A1-A5 & B kg CO_2	LCC Total NPV SEK / m2	SPR [-]
Scenario 01	Glass wool	Preinsulated Duct	Swedish Concrete	48.41	2.10E+02	3,655	0.9228191
Scenario 02	Mineral Wool	Preinsulated Duct	Swedish Concrete	48.41	2.12E+02	3,788	0.9338606
Scenario 03	Wood Fibre 20 cm	Preinsulated Duct	Swedish Concrete	49.33	1.91E+02	4,134	0.9231376
Scenario 03-Improved	Wood Fibre 25 cm	Preinsulated Duct	Swedish Concrete	48.39	1.84E+02	4,208	0.9102704
Scenario 04	Cellulose	Preinsulated Duct	Swedish Concrete	48.85	2.02E+02	3,807	0.9194566
Scenario 05	Glass wool	Spiral Duct Steel	Swedish Concrete	48.31	2.12E+02	4,042	0.9507635
Scenario 06	Mineral Wool	Spiral Duct Steel	Swedish Concrete	48.31	2.13E+02	4,175	0.9618050
Scenario 07	Wood Fibre 20 cm	Spiral Duct Steel	Swedish Concrete	49.23	1.93E+02	4,521	0.9510266
Scenario 07-Improved	Wood Fibre 25 cm	Spiral Duct Steel	Swedish Concrete	48.28	1.86E+02	4,596	0.9381433
Scenario 08	Cellulose	Spiral Duct Steel	Swedish Concrete	48.74	2.03E+02	4,193	0.9471803
Scenario 09	Glass wool	Preinsulated Duct	Romanian Concrete	48.41	2.12E+02	3,634	0.9244367
Scenario 10	Mineral Wool	Preinsulated Duct	Romanian Concrete	48.41	2.13E+02	3,767	0.9354782
Scenario 11	Wood Fibre 20 cm	Preinsulated Duct	Romanian Concrete	49.33	1.92E+02	4,113	0.9247552
Scenario 11-Improved	Wood Fibre 25 cm	Preinsulated Duct	Romanian Concrete	48.39	1.86E+02	4,187	0.9118880
Scenario 12	Cellulose	Preinsulated Duct	Romanian Concrete	48.85	2.03E+02	3,786	0.9210741
Scenario 13	Glass wool	Spiral Duct Steel	Romanian Concrete	48.31	2.14E+02	4,022	0.9523811
Scenario 14	Mineral Wool	Spiral Duct Steel	Romanian Concrete	48.31	2.15E+02	4,154	0.9634226
Scenario 15	Wood Fibre 20 cm	Spiral Duct Steel	Romanian Concrete	49.23	1.94E+02	4,500	0.9526442
Scenario 15-Improved	Wood Fibre 25 cm	Spiral Duct Steel	Romanian Concrete	48.28	1.88E+02	4,575	0.9397609
Scenario 16	Cellulose	Spiral Duct Steel	Romanian Concrete	48.74	2.05E+02	4,172	0.9487979
Scenario 17	Glass wool	Preinsulated Duct	Green Concrete-Skanska	48.41	2.09E+02	3,681	0.9222151
Scenario 18	Mineral Wool	Preinsulated Duct	Green Concrete-Skanska	48.41	2.10E+02	3,814	0.9332566
Scenario 19	Wood Fibre 20 cm	Preinsulated Duct	Green Concrete-Skanska	49.33	1.89E+02	4,160	0.9225336
Scenario 19-Improved	Wood Fibre 25 cm	Preinsulated Duct	Green Concrete-Skanska	48.39	1.83E+02	4,235	0.9096664
Scenario 20	Cellulose	Preinsulated Duct	Green Concrete-Skanska	48.85	2.00E+02	3,834	0.9188526
Scenario 21	Glass wool	Spiral Duct Steel	Green Concrete-Skanska	48.31	2.11E+02	4,069	0.9501595
Scenario 22	Mineral Wool	Spiral Duct Steel	Green Concrete-Skanska	48.31	2.12E+02	4,202	0.9612010
Scenario 23	Wood Fibre 20 cm	Spiral Duct Steel	Green Concrete-Skanska	49.23	1.91E+02	4,547	0.9504226
Scenario 23-Improved	Wood Fibre 25 cm	Spiral Duct Steel	Green Concrete-Skanska	48.28	1.85E+02	4,623	0.9375393
Scenario 24	Cellulose	Spiral Duct Steel	Green Concrete-Skanska	48.74	2.02E+02	4,220	0.9465763

Figure 9: Calculated values of SPR for each scenario, EP_{pet} (30%), LCA (40%), LCC (30%)

Scenario	Insulation	Duct Type	Concrete Type	Primary Energy EPpet kWh/m² yea	LCA GWP Per A1-A5 & B kg CO_2	LCC Total NPV SEK / m2	SPR [-]
Scenario 01	Glass wool	Preinsulated Duct	Swedish Concrete	48.41	2.10E+02	3,655	0.9040749
Scenario 02	Mineral Wool	Preinsulated Duct	Swedish Concrete	48.41	2.12E+02	3,788	0.9173807
Scenario 03	Wood Fibre 20 cm	Preinsulated Duct	Swedish Concrete	49.33	1.91E+02	4,134	0.9238380
Scenario 03-Improved	Wood Fibre 25 cm	Preinsulated Duct	Swedish Concrete	48.39	1.84E+02	4,208	0.9155888
Scenario 04	Cellulose	Preinsulated Duct	Swedish Concrete	48.85	2.02E+02	3,807	0.9079978
Scenario 05	Glass wool	Spiral Duct Steel	Swedish Concrete	48.31	2.12E+02	4,042	0.9395553
Scenario 06	Mineral Wool	Spiral Duct Steel	Swedish Concrete	48.31	2.13E+02	4,175	0.9528611
Scenario 07	Wood Fibre 20 cm	Spiral Duct Steel	Swedish Concrete	49.23	1.93E+02	4,521	0.9592557
Scenario 07-Improved	Wood Fibre 25 cm	Spiral Duct Steel	Swedish Concrete	48.28	1.86E+02	4,596	0.9510105
Scenario 08	Cellulose	Spiral Duct Steel	Swedish Concrete	48.74	2.03E+02	4,193	0.9432268
Scenario 09	Glass wool	Preinsulated Duct	Romanian Concrete	48.41	2.12E+02	3,634	0.9045033
Scenario 10	Mineral Wool	Preinsulated Duct	Romanian Concrete	48.41	2.13E+02	3,767	0.9178091
Scenario 11	Wood Fibre 20 cm	Preinsulated Duct	Romanian Concrete	49.33	1.92E+02	4,113	0.9242664
Scenario 11-Improved	Wood Fibre 25 cm	Preinsulated Duct	Romanian Concrete	48.39	1.86E+02	4,187	0.9160172
Scenario 12	Cellulose	Preinsulated Duct	Romanian Concrete	48.85	2.03E+02	3,786	0.9084262
Scenario 13	Glass wool	Spiral Duct Steel	Romanian Concrete	48.31	2.14E+02	4,022	0.9399837
Scenario 14	Mineral Wool	Spiral Duct Steel	Romanian Concrete	48.31	2.15E+02	4,154	0.9532894
Scenario 15	Wood Fibre 20 cm	Spiral Duct Steel	Romanian Concrete	49.23	1.94E+02	4,500	0.9596841
Scenario 15-Improved	Wood Fibre 25 cm	Spiral Duct Steel	Romanian Concrete	48.28	1.88E+02	4,575	0.9514389
Scenario 16	Cellulose	Spiral Duct Steel	Romanian Concrete	48.74	2.05E+02	4,172	0.9436552
Scenario 17	Glass wool	Preinsulated Duct	Green Concrete-Skanska	48.41	2.09E+02	3,681	0.9046255
Scenario 18	Mineral Wool	Preinsulated Duct	Green Concrete-Skanska	48.41	2.10E+02	3,814	0.9179313
Scenario 19	Wood Fibre 20 cm	Preinsulated Duct	Green Concrete-Skanska	49.33	1.89E+02	4,160	0.9243886
Scenario 19-Improved	Wood Fibre 25 cm	Preinsulated Duct	Green Concrete-Skanska	48.39	1.83E+02	4,235	0.9161394
Scenario 20	Cellulose	Preinsulated Duct	Green Concrete-Skanska	48.85	2.00E+02	3,834	0.9085484
Scenario 21	Glass wool	Spiral Duct Steel	Green Concrete-Skanska	48.31	2.11E+02	4,069	0.9401059
Scenario 22	Mineral Wool	Spiral Duct Steel	Green Concrete-Skanska	48.31	2.12E+02	4,202	0.9534116
Scenario 23	Wood Fibre 20 cm	Spiral Duct Steel	Green Concrete-Skanska	49.23	1.91E+02	4,547	0.9598063
Scenario 23-Improved	Wood Fibre 25 cm	Spiral Duct Steel	Green Concrete-Skanska	48.28	1.85E+02	4,623	0.9515611
Scenario 24	Cellulose	Spiral Duct Steel	Green Concrete-Skanska	48.74	2.02E+02	4,220	0.9437774

Figure 10: Calculated values of SPR for each scenario, EP_{pet} (30%), LCA (30%), LCC (40%)

6.4 Hygrothermal Performance Assessment

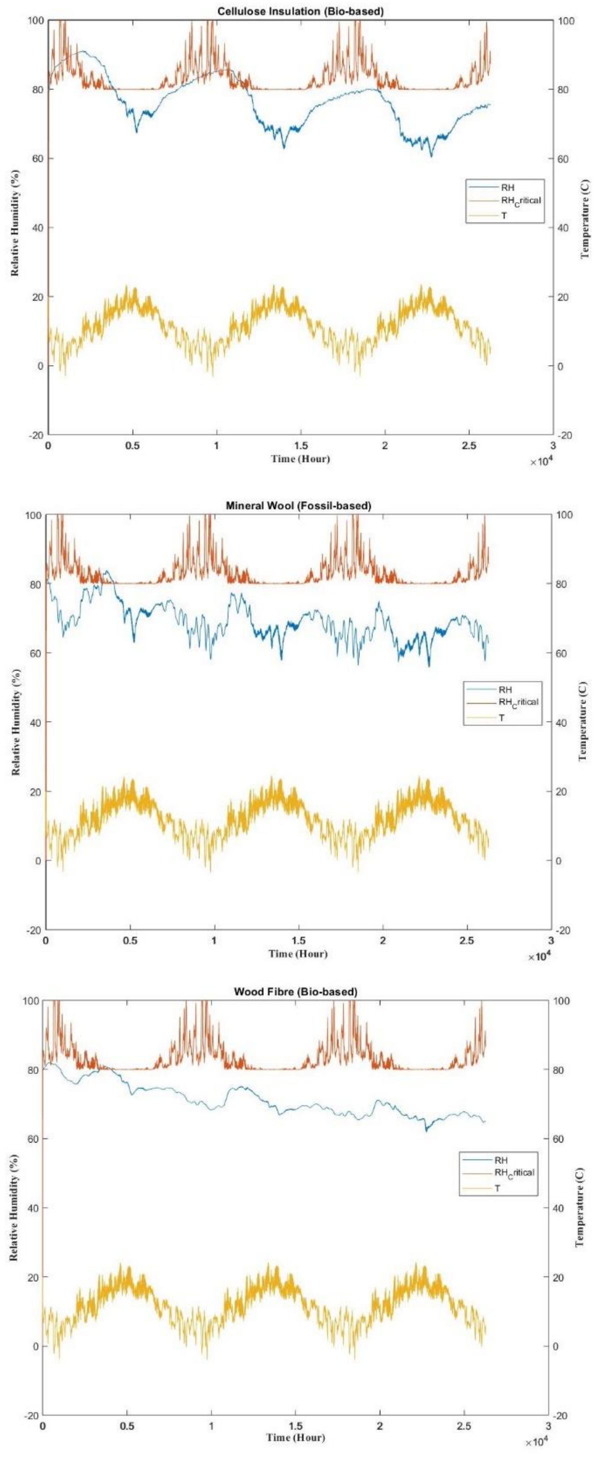

Figure 11: Hygrothermal analysis for 3 thermal insulation materials

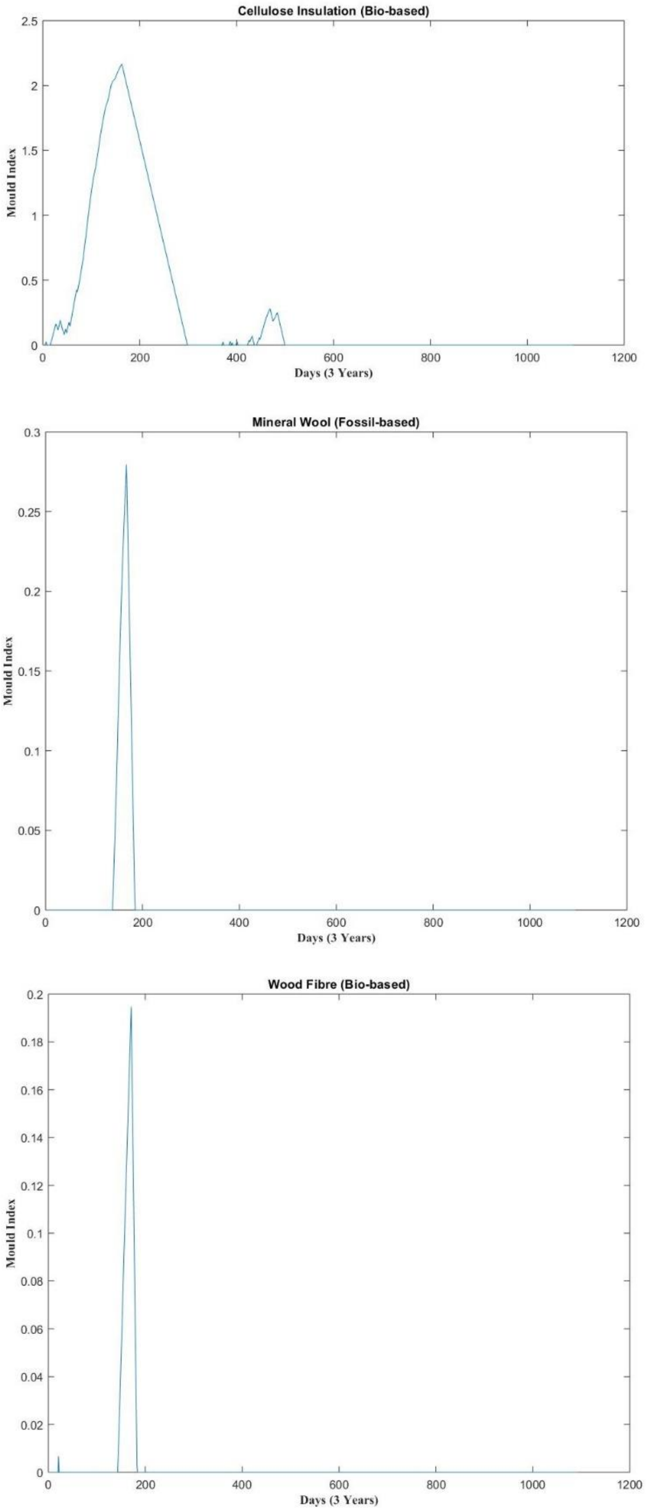

Figure 12: Mould index calculations based on VTT model

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