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Parametric study of energy retrofit options for a historical building

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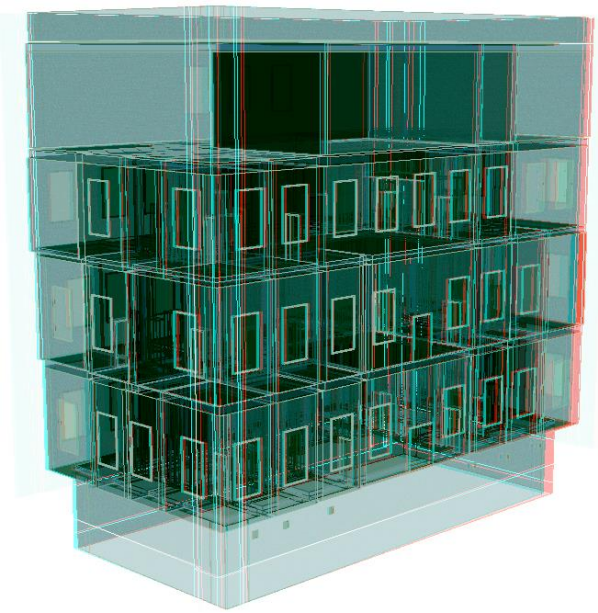

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Cover picture: The IDA-ICE model of the “Rådhuset” with a transparent view of the inner rooms and spaces that were part of the simulation.

Preface

This work would have never been possible without the love and support of my better half, my life's best teammate and partner in crime.. My Dear wife Mrs. El Tayara.

I would also like to thank my supervisor Arman for his guidance, patience and for giving me this opportunity to work on this thesis.

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Abstract

Retrofitting measures in old buildings aimed at reducing energy consumption has become a widespread subject and an urgent matter to counteract the effects of climate change and GHGs emissions. The globe has reaffirmed its agreement taken in COP21 to reduce emissions in COP26. The building sector is one of the culprits with a 70 % future energy consumption forecasted by 2050 i.e., the year certain countries aim to carbon neutral (e.g., Sweden). An old building with a severe problem of energy leakage has been studied under the influence of multiple parameters such as building orientation, shading systems, location, Low-E film and an alternative energy supply (GHP). The original building's EnU amounted to 194.5 kWh/m^2•yr; the parameters were applied and orientation of 90^0 worked best, if the building was being designed, contrary to this case. However, energy reductions, compared to the base model, were actually achieved with the application of Low-E (5%) films and when substituting the heating demand with a GHP (57.5%), LEF-GHP reached (59.2%) and a corresponding decrease in CO_2 emissions. Thermal comfort was best achieved with models that had the highest energy consumption such as LEF and ES making it counterproductive in fulfilling the aim of reducing GHG footprint of Rådhuset. The economic feasibility study showed that the installation of a GHP with at least the COP of 4.0 would lead to a shorter payback period than solely applying LEF. A tailored solution of a change in the energy source such as electrified heat supply from renewables combined with LEFs would reduce the energy and emission impact of any building; this would help the building sector reach the envisioned goal of carbon neutrality in 2050.

Keywords: Energy Retrofitting, Building Performance, Thermal Comfort, Shading, Building Orientation, Location, Low-E films, Solar Gains

Nomenclature

Abbreviation	Description	Unit
SHG	Solar Heat Gain	kWh/yr.
SHGC	Solar heat gain coefficient	
BEP	Building Energy Performance	
GHP	Geothermal Heat Pump	
EnU	Energy Usage	kWh/yr.
GHGs	Greenhouse Gases	
WWR	Window Wall Ratio	%
TC	Thermal Comfort	
LEF	Low-E film	
IS	Internal Shading	
ES	External Shading	
PMV	Predicted Mean Vote	
PPD	percentage of total occupant hours with thermal dissatisfaction	%
DH	District Heating	
COP	Coefficient Of Performance	
PBT	Undiscounted Payback Time	years
DPB	Discounted Payback Time	years
CF	Cash Flow	€
NPV	Net present value	€
D%	Discount rate	%
SH	Southern Hemisphere	
NH	Northern Hemisphere	
CAV	Constant Air Volume	$L/s.m^2$
AHU	Air Handling Unit	
SMHI	Swedish Meteorological and Hydrological Institute	
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers	
CME	Comfort per Metered Energy	$\%/kWh/m^2 \cdot yr$
TDE	Total Delivered Energy	kWh/yr.

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1 Introduction

Retrofitting measures in old buildings aimed at reducing energy consumption has been gaining ground due to reasons explained in section 1.3. In this study windows will constitute the largest portion of this retrofit parametric evaluation along with changing the energy supply source. The energy consumption, comfort and feasibility were monitored.

Windows in a building are perforation in the envelope that provides occupants with protection against the elements. They satisfy a need for dwellers to enjoy the bounties of the outside world such as fresh air, daylight and a view from the safety of their home that helps in psychological and physical healing [1]. They impart a positive psychological effect on humans [2].

Researchers, however, have pointed out windows' poor energy performance due energy losses/gains by transmission along with the passive solar heat gains that could impact the heating/cooling loads differently depending on the location and/or time of the year [2] [3]. It will be seen later on how windows can affect the buildings' energy consumption depending on different crucial factors that will be explained later in the document.

1.1 Background

Global warming and climate change are two of the most important challenges in the age of modern humans. Scientists and experts have showed concerns about the probability of an irreversible transformation of the planet in the near future [4]. The Intergovernmental Panel on Climate Change (IPCC) has unanimously agreed that warming of the Earth's different biospheres was due to an increase in the concentrations of greenhouse gases (GHGs) because of anthropogenic activities [4].

Efforts to counter climate change were crowned by and international effort in the Paris agreement at Paris COP21 in 2015 and later in COP26 in 2021 at Glasgow that gave birth to the "Glasgow climate pact" and the final enhanced form of the "Paris Rulebook" [5] (the detailed rules that make the Paris Agreement operational):

- agreeing to the 'enhanced transparency framework' (common reporting of emissions and support)
- a new mechanism and standards for international carbon markets
- and common timeframes for emissions reductions targets

Most of the global energy consumption has its sources in fossil fuel, such as natural gas and coal, to mention a few, which are deemed harmful to the environment and consequently for humans [6] [7]. This resulted in an urgency to mitigate the effects of global warming and climate change by implementing rapid, deep and sustained reductions in GHGs emissions; this included reducing the global carbon dioxide emissions by 45 % by 2030 to the levels of 2010 [5] [6]. One of the sectors responsible for almost 40 % of the global energy consumption is the building sector. The energy consumption is expected to increase by a rate of 3% per year and is forecasted to reach 70% by 2050 [5] [6] [8].

The IEA report expects that a building floor area the size of Paris would be added globally on a yearly basis from 2020 to 2050 in developing economies, such as eastern Europe, southeast Asia and in the middle east [9]. In more developed economies it is expected that more than half the

building stock will be standing in 2050. Most of the buildings in the world belong to the residential sector that have a 22% share of the global energy consumption and are built before the 1970 and 25 % of that stock were built in the prior the middle of the last two centuries and are considered to be a symbol of Europe's cultural heritage [2] [6] [10] [11] The demand for energy in buildings is expected to increase to 28 % by 2030 due to population growth and higher living standards [6][11][12].

There is a need to reduce energy usage and to improve the energy efficiency in the existing building stock by the means of retrofit techniques and measures [7]. It is known that buildings are affected by global warming during their lifespan due to changes in the outdoor conditions resulting in a degradation in BEP and thermal comfort [4]. That is why emissions (that arise primarily from the demand for space heating and cooling from the building stock needs to be reduced throughout their lifecycle through a dedicated strategy that reduces energy demand (behavioral change and energy efficient) and electrification through renewable sources (decarbonization) [10]. This would make it possible to achieve carbon neutrality by 2050 [9] [13]. This is considered to be a key factor in the evaluation of sustainable living [4]; as well as play a significant role in enhancing the national energy security, reduce vulnerability to energy prices and increase human comfort and productivity [7].

A building is better described as the shelter that protects its inhabitants from the extremes of the surrounding environment such as heat, cold, wind and rain [3] [14]. This establishes an interrelationship between the dwelling and the dwellers in the form of interactions with the building envelope, the HVAC system and the occupants (occupant behavior, operating hours and number of appliances within the envelope) An interrelationship that could lead to high cooling/heating demands when the building comes out short in sustaining thermal comfort to its dwellers, which translates into a rise in energy demand. [14] [15].

As mentioned in the introduction that most of the buildings in Europe are in need of a fundamental retrofit to improve building performance and thermal comfort. The modernization step might face barriers such as loss of capital, market disruption, volatile energy prices or an epidemic such as Covid-19 (which resulted in a global financial crisis), extended payback periods as well (and most importantly) the willingness to pay for a retrofit that could, on the long run, reduces cost, emissions and increase occupant comfort [3] [7]. This makes it imperative to plan a long-term strategy for building retrofit with periodic energy audits to ensure both building performance and thermal comfort [7].

1.2 Object of study

A City Hall or Rådhuset is a three-level concrete building situated in Gävle, Sweden. It was built in the late 1700s and today it is being used as an office building for the municipality of Gävle. In [2] it was mentioned that the building was classified as a historical structure and as a result follows very strict retrofitting regulations forbidding any modifications to the external envelope of the building. The building has a total of 76 double glazed windows (71 in the IDA-ICE model) with wooden frames which constitute 11.7% (10.9% in the model) window-wall-Ratio (WWR). Fig.1 shows the northern side of the building towards the square and the concrete façade of the building. A local district heating facility satisfies the heating energy for space heating (radiators and heating coils) and for domestic hot water powered by "fuel" in the model. [2]

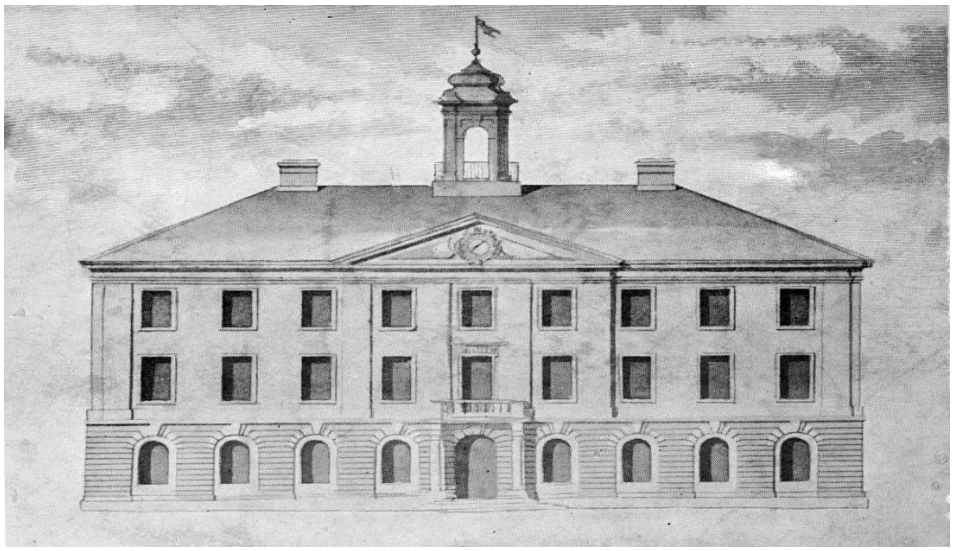

Figure 1: Sketch of Rådhuset in Gävle from 1782 [16]

Old buildings, the historic object in this study, were built to last i.e., Durability, functionality and mechanical reliability with thermal comfort being of a much lesser importance [2]. EnU in a building is dependent on a whole host of factors such as:

- Geographical location and climate
- Wind profile (urban, costal, rural)
- Infiltration (leakages in/out the envelope)
- Pressure coefficient
- Building material
- Occupancy (number of occupants and the time they spend within the confines of the envelope)
- Operating hours
- Electric appliances
- Thermal Mass (internal thermal mass like furniture, Thickness of the envelope and building material)

Structures are uniquely characterized by the building geometry, material in the core and envelope (wood, concrete, steel), location, climate zone, orientation (depending on NH or SH) and surrounding conditions [11]. Special significance is usually given to the envelope and windows and their relationship represented in WWR when assessing EnU and BEP. The U-value (how much heat is transferred through the window in $W/(m^2 \bullet K)$ described in section 2.1) of both envelope and window and the type of glazing; the latter has great implications to the cooling/heating loads in any climate [11] [14]. Windows are an important part of a building design providing natural light, ventilation and has a positive psychological effect on occupants [1] [2] [17]. Windows exchange energy with the outer environment through different physical processes [3]:

1- Conduction
2- Convection
3- Radiation
4- Leakage/infiltration

1.3 Scope and Limitations

The system boundary of this study was the building envelope. The factors examined were the energy usage (EnU) and solar heat gains (SHG)s with focus on building energy performance (BEP), thermal comfort (TC) and economic feasibility.

The model was handed over from the previous researchers and was studied with no other changes beyond those mentioned in section 1.2 and in more details in Chapter 3. That was done to enable a sound comparison with the model in [2].

1.4 Aim

The main goal was to examine the changes in energy performance and thermal comfort by retrofitting the building in [2] (that was already validated in the study of "Low-E"), with certain parameters such as:

- Façade Orientation
- Window shadings
- Locations
- Alternative energy supply. Geothermal heat pump (GHP)

A secondary goal was to investigate the economic feasibility of the investment in the newly added parameters if the implemented parameter results in energy savings i.e., a successful reduction in EnU. The results of [2] will also be assessed to the new energy prices of 2022 (see Tab.1 appendix C).

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2 Theory

BEP and TC could be enhanced if the processes that affect them were identified and understood. In the following text the main phenomenon that took part in the simulation are given a place in the spotlight. This section should prepare the reader for the ideas and theories that were included into the study directly or indirectly.
The focus of this part is to display the science behind solar energy versus heat gains in buildings and the parameters mentioned earlier in the introduction. A background about district heating, GHG emissions and geothermal heat pumps (GHP). It is important to understand these processes when designing or optimizing (retrofitting) a building. Having a firm grasp of these phenomena will ensure an efficient BEP and TC.

2.1 Transfer of thermal energy through a building

Energy transfers from one location to another in different modes:

- **Radiation**: the transfer of energy by means of electromagnetic waves that energize the particles of the incident object in which part of that energy is absorbed, reflected or radiated out in the form of longer waves and of lower energy content than the original state of the incident electromagnetic radiation. [3] [18]
- **Convection**: is the transfer of energy (transfer of enthalpy) through the motion of fluids (air, water) as they come in close contact with a medium (surface or another fluid) with higher thermal energy content, the fluid particles then gain kinetic energy and spread out causing a decrease in density and an upward flow giving way to convection currents.
- **Conduction**: heat transfers through matter direct contact with a medium. Energy will move by conduction through solids, e.g., walls, which are in contact and are of different energy levels. [3] [18]

These modes of energy transfer can be seen interacting with a structure, e.g., a house, in Fig.2.

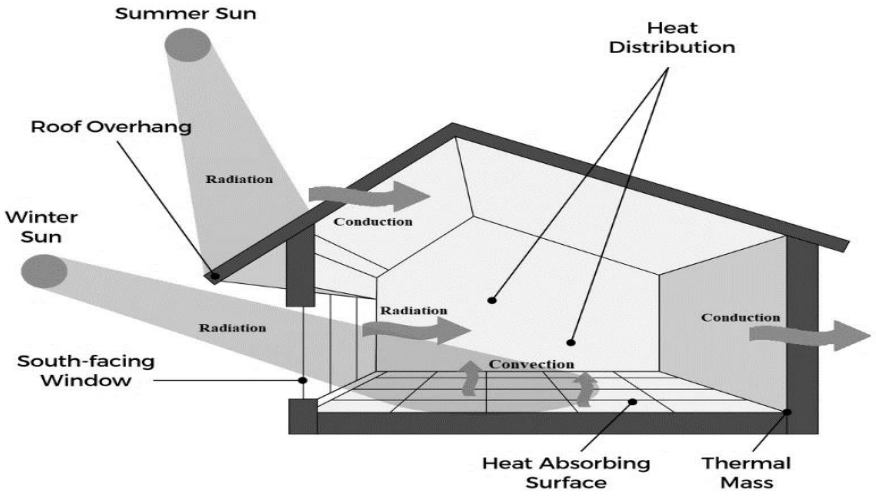

Figure 2: Thermal energy transfer modes along with solar position in the NH. (Modified from [19])

Different materials, e.g., that constitute a building envelope, have a certain property that affects the magnitude of the thermal flux passing through them termed the *thermal resistance* **R** measured in $m^2.K/W$. It is a parameter that is used where the insulation properties are important [3] [20]. Composite part of the envelope will have different Rs depending on the thickness, material and the area of the different layers as seen in Fig.3.

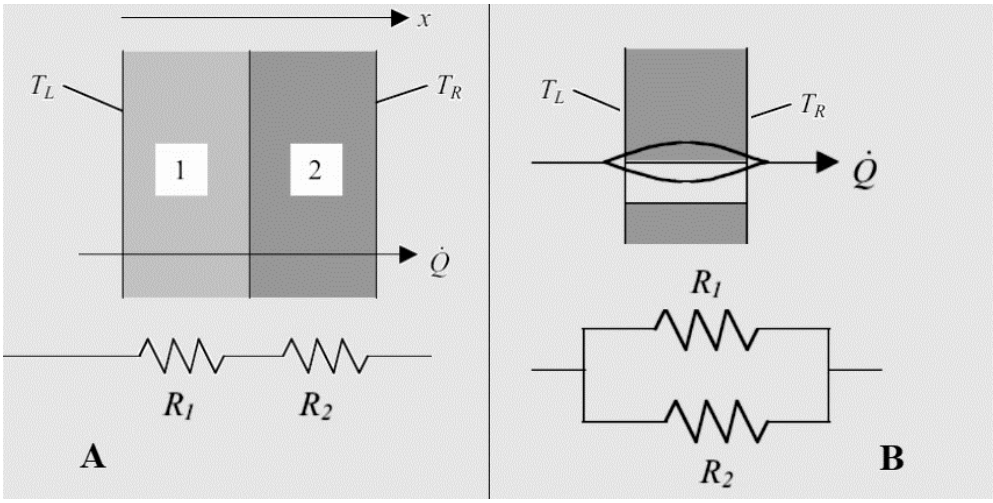

Figure 3: the different modes to calculate thermal resistance depending on the position and orientation of the layers. (A) shows a series coupled layers while (B) shows a parallel coupling.[18]

The inverse of the total thermal resistance is called the *thermal transmittance* [3] [18] i.e., U-value; it is used to calculate the transfer of thermal energy through the building envelope especially windows [18] [20]. The simplified equation is another form of Fourier's law and takes the form of

$$\boldsymbol{Q = U_{corr}(T_i - T_e)} \qquad \text{Eq (1)}$$

Q:	Heat transfer through the envelope in W/m^2
U_{corr}:	Corrected thermal transmittance in $W/m^2.K$
T_i:	The indoor temperature in K
T_e:	The exterior or Outdoor temperature in K

Equation (1) makes it possible to impact the amount of transferred energy Q by making certain changes to U (corr is dropped for simplicity) in an environment of the same temperature profile or patterns like seasonal changes in temperature and solar angles [3] [21].

Solar energy is one of the driving forces behind internal heat gains [3][18]. It passes through the envelope by all the three main modes of heat transfer mentioned before. In a building window, which are perforations in the envelope responsible for both heat gains and losses, become important to determine the WWR which is the total glazing area per area of building envelop [3] [18].

The transfer of solar energy through the window layers are partially absorbed into the inside of the building, the ratio of the solar radiation that is incorporated into the internal space to the total incident solar radiation unto the window area is defined as the solar heat gain coefficient (SHGC) or g-value; In IDA ICE the g-value is denoted as the fraction of the radiation, incident on the window, that heats the room. SHGC includes both the radiation that passes through the window directly and the radiation that is first absorbed in the panes and thereafter reaches the zone as convection and long-wave radiation (see Fig.4); SHGC is represented in equation 2 [3].

$$\boldsymbol{SHGC\ or\ g-value} = \frac{\boldsymbol{Solar\ radiation\ through\ a\ window}}{\boldsymbol{Solar\ radiation\ incident\ on\ the\ window}} \qquad \textit{Eq (2)}$$

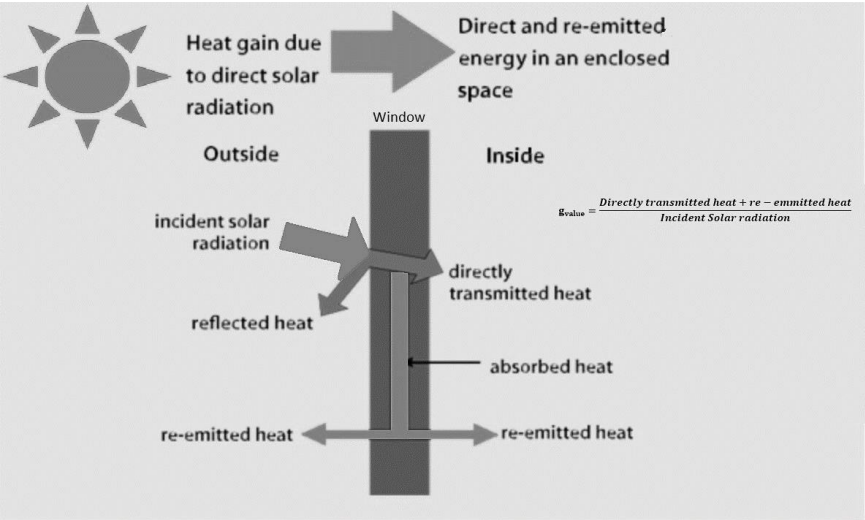

Figure 4: Solar heat gain through a window with a simplified expression of SHGC or g-value. (Modified from [22])

In cold countries it is suitable to have a low U-value to prevent thermal energy leakage through transmission and relatively high g-value to let in solar radiation to heat the insides of a room, thus reducing the need for heating, however there is a risk of overheating during hot days. The opposite is true for buildings in warmer climate [3].

2.2 External Heat Gain/losses

A consequence of global warming is the gradual increase of the global demand for space cooling with an opposite trend for the demand of space heating [4]. There are, of course, significant differences between climate zones noting that most of the energy used for space cooling/heating still comes from non-renewable sources, hence a growth in the total emissions of GHGs [4] [5]. To develop methods and means to decrease the cooling/heating demand in a building, a light is shed upon the energy gains in the structure. Buildings have internal heat gains (occupants, appliances,

lighting, HVAC) and external heat gains due to solar energy which penetrates the envelope through the walls and windows (mainly) [3].

Internal heat gains are the thermal energy emitted to the air by the occupants via their metabolism and level of activities indoors as well as their usage of lighting and appliances, i.e., behavioral effect on internal heat gains. There is also the heat emitted indirectly from the walls due to thermal mass that determines the capacity of a building to store heat energy which influences the indoor temperatures and consequently the thermal comfort; in this study the building has a high thermal mass. [3] [23] [24].

External heat gains are driven by the solar energy of the sun when the incident solar radiation strikes the outer walls and is transferred by conduction followed by convection into the room, this depends of course on the thickness and material composition of the envelope. Solar radiation through windows is the main source of direct external heat gains as the sun rays strike the surfaces inside the room they are converted into heat and raise the temperature of the air and as a result of radiation-convection-conduction interactions the air heats up and later on the rest of the room [3] [23].

The sun angle, or solar elevation angle, is location and time dependent and must be taken into consideration when assessing the magnitude of external heat gains [15]. The variation in location, as seen later on in this paper, have huge implications if LEFs and shadings are feasible to implement. This is due to the corresponding variation in the zenith, azimuth and solar elevation angles among different geographical locations [15] [23] (see Fig.5 and Fig.21).

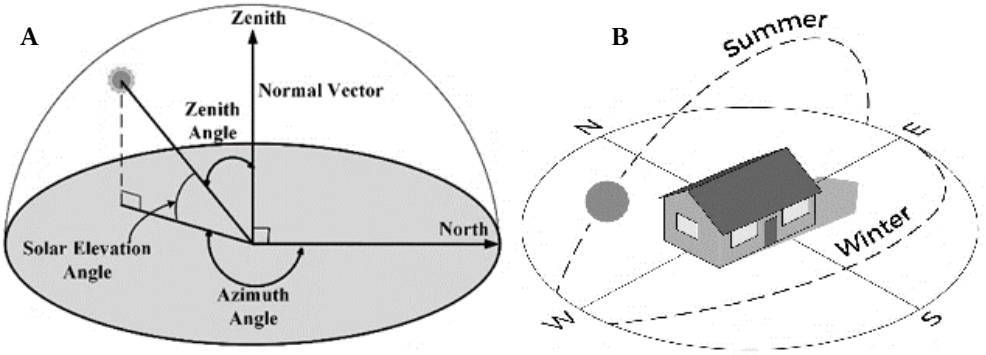

Figure 5: (A) The different solar angles between the surface and the sun; (B) the effect of solar angles during the different seasons i.e., during the summer and winter solstice [19] [25]

Windows have been confirmed as being a large contributor to the substantial energy exchange between the indoor and outdoor environment whether it was heat gains or losses, again depending on location, orientation and the time of the year [15] [23] [26]. Understanding such interactions have the potential to result in tailored solutions that reduce EnU, lead to electricity savings and reduction in GHGs emissions; for example, the energy consumption for a building with large WWR in cold climates can be reduced by simply applying solar control measures with Low U-value and a moderate SHGC and vice versa in hot climates [2] [15].

2.3 Location

The surrounding environment in which a building exists has a definite effect on the amount of internal and external heat gains. Location specifications such as longitude and latitude have implications on climate behavior through seasons driven by the position of the sun during the seasonal tilt of earth [3]. According to the Köppen-Geiger the globe is classified into thirty climate types according to three categories: Main climate, Precipitation and Temperature as seen in Fig.6 [26]

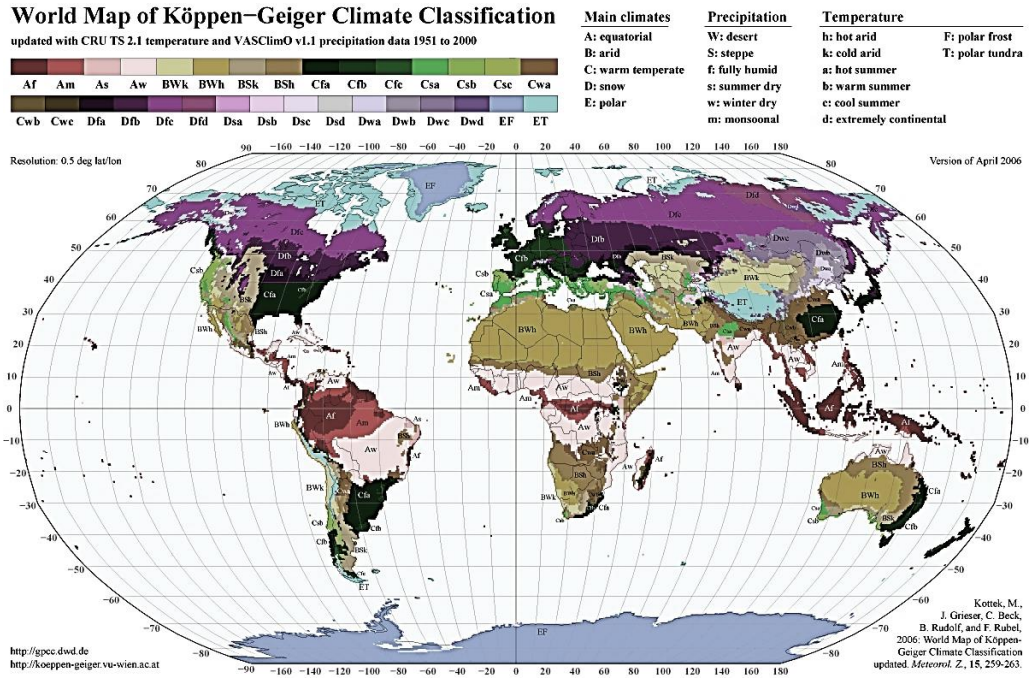

Figure 6 World map according to Köppen-Geiger climate classification. The letters a the top left have their description at the top right. The color codes and the map are used as a visual aid [26]

This presents a challenge when constructing or retrofitting buildings that are supposed to provide comfortable living conditions around the world due to the numerous weather patterns and solar intensities [12] [15]. Warmer climates need to limit the external heat gains by solar control technologies to offset higher solar radiation exposure and reduce the cooling load subsequently resulting in energy savings [17]. In colder climate the intention is to limit the envelope losses and reduce the heat load resulting in energy savings [2].

2.4 Orientation

Orientation is one of the most important parameters and is a low-cost option (during the design-stage) that influences TC and EnU which makes it a major step when planning a habitat [8] [28] [29]. Changing the orientation of a building is mostly limited to simulations and to houses, which is why it is imperative that accurate simulations, which are location related, be run before construction ensuring a maximum solar gain in the heating season and a minimum in the cooling season [8] [30].

In the NH in regions characterized by a cold climate (Sweden) it is found that orientating the floor plan so that the most frequently used rooms (living room, bedrooms and kitchen) is facing south results in favorable external heat gains while in the SH (Australia) the northern orientation achieves similar favorable results (see Fig.7) [8] [29] [31] [32].

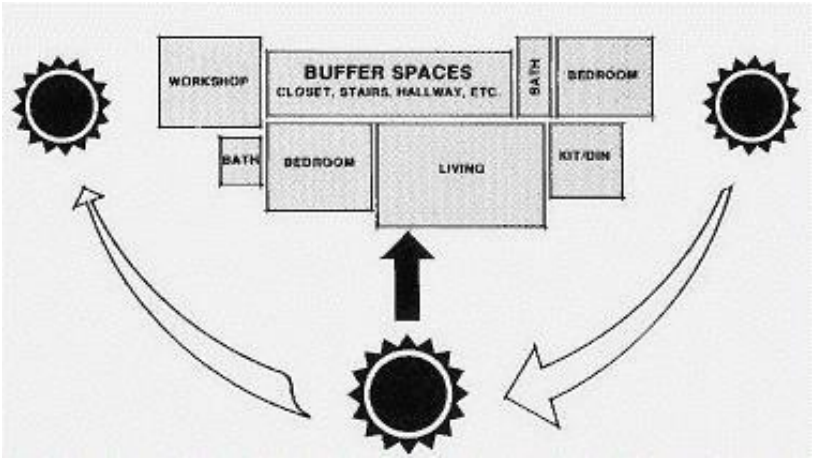

Figure 7: Room setup with respect to the façade with the best SHGs according to rule of thumb that spaces with highest occupancy should face the side with highest solar heat gains. [32]

2.5 Shading

Shading devices are considered to be part of the solar control system and are crucial in improving the level of TC and reducing EnU [23][33]. It is one of the most common ways to achieve a low-cost decrease in indoor temperature and reducing the cooling load during the cooling season in hot and dry climates; they are also manipulated (if they are movable or manual) to increase the area through which solar radiation enters during the heating season to make use of external heat gains due to solar radiation, thus decreasing the heating load. [33]. Shading has a drawback that it could decrease incoming daylight which causes occupants to use extra lighting leading to a change in the overall energy savings [31].

Shading devices are of two types internal and external shading devices depending on the location they are installed. They are manual, fixed, or movable based on the manner of operation [15][33].

2.5.1 Internal Shading

Internal Shading (IS) devices, such as curtains, are used internally within the confinement of the room or between windowpanes in multi-glazed fenestrations to block incoming solar radiation when needed. Based on their type (clear or dark, lightly woven or thick) and material (textile, thin wooden laminate) they could contribute differently to the cooling load reduction during the cooling season. They do that by adjusting the U-value of the window by decreasing it [34][14].

A draw back to IS devices was found that they could raise the indoor temperature and increase the cooling load. This occurs due to the existence of a cavity between the windows inner surface and the curtain where the air is heated and transmits heat via convection to the internal thermal environment. As mentioned before the material that makes up the IS heats up by absorbing part of the incident solar radiation and then emits the heat through long wave thermal radiation, thus adding to the internal heat gains. [34]

2.5.2 External Shading

External shading (ES) devices are installed at the out façade of the building envelope. They are used to block direct incident solar radiation and reduce the influence of diffuse and reflected radiation. ES could be of the materials mentioned in the previous section and take the form of overhangs, awnings or louvre (see Fig.8). If the ES is movable or manual then they could be adjusted to exclude or admit solar radiation (daylight) on demand [12] [35]. Research that is related to ES found that increase of latitude shading on the south windows performed better (in the SH) and that ES are required for energy savings and reducing cooling load of buildings [12].

ES do not suffer from the IS drawbacks, in fact it has been demonstrated that the ES provide the highest energy savings in the cooling season in warm/hot climate [12] [23] [35].

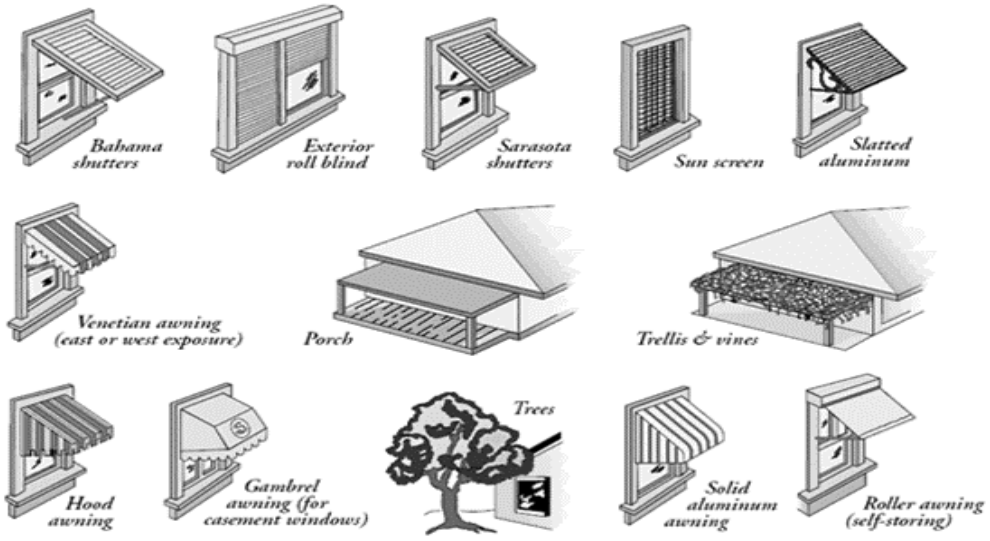

Figure 8 different types of external shadings and their corresponding names. [36]

2.5.3 Low-E Films

LEFs are a type of advanced material that are spectrally selective designed to prevent the near infra-red radiation of the sun and are used on windows to improve TC and BEP. They are characterized with low U-value and relatively low SHGC or g-value which is how much solar radiation passes through a glazing and is released as heat indoors [3] [11] [18]. These films are easy to use on already existing windows, such as the object of this study, as they are less intrusive and less complicated to apply enabling the user to mitigate EnU without compromising the benefits of natural light into the confined space of a room. A tailored LEF should, according to [2] improve window insulating performance that leads to an enhanced TC. This result is also shared by [17] that solar films have the potential to aid in energy savings in buildings especially in hot climates [37].

2.6 Thermal Comfort

Occupants are affected by the indoor environment that they live in, such as air (temperature, humidity and velocity) and mean radiant temperature, as it impacts their sense of comfort by positively complementing the thermal energy balance of their bodies. This balance is also influenced by their physical activity clothing [38]. Another important factor is the ventilation, ventilation flowrate and the air distribution system [39][40]. Although there are some newly developed systems available, such as impinging jet ventilation and stratum ventilation system [41][42][43], in this study the assumption is that the building is using a mixing ventilation system.

A method that was developed by Fanger 1972 allows for the prediction/estimation of the thermal sensation for the body as a whole to determine the predicted mean vote or (PMV) on a seven-point thermal sensation scale as shown in the following table (Tab.1). [38] [44]

Table 1: PMV 7-point scale

-3	-2	-1	0	+1	+2	+3
Cold	Cool	Slightly cool	Neutral	Slightly Warm	Warm	Hot

The values of PMV are then used to quantitatively estimate the number of thermally dissatisfied occupants in a given space namely the predicted percentage dissatisfied (PPD). In short dissatisfaction or comfort limits can be expressed by the PMV and PPD. The later provides information about the partition of occupants that feel too cold/warm in a room see Fig.9.

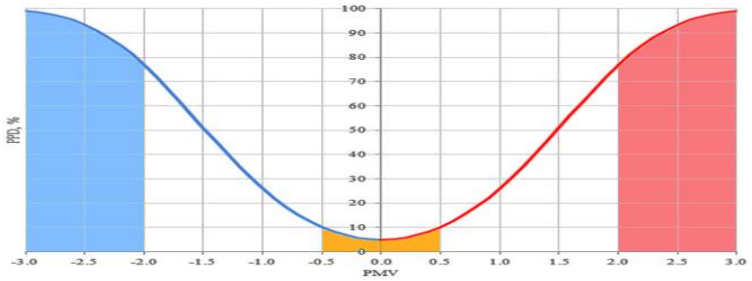

Figure 9: Relationship between PMV and PPD [38][45]

2.7 District heating and GHG emissions

District heating (DH) is one of the energy supplies that are handled in this study. DHs have become an important part of harvesting their environmental benefits in reducing GHG emissions which is one of the main goals in fighting climate change. This can be done according to [46] in two ways: (1) Accelerating the utilization of non-fossil energy forms for heating/cooling, (2) Using better central heating systems that have superior efficiency instead. DH have proven to be flexible when it comes to fuel sources to produce energy; they are, however, not perfect even though they might be utilizing biomass and waste, and thus reducing the use of non-renewables, there are still the concerns of air quality, CO_2 emissions from DH and the transportation of the forementioned fuel to the DH facility see Fig.10 [47].

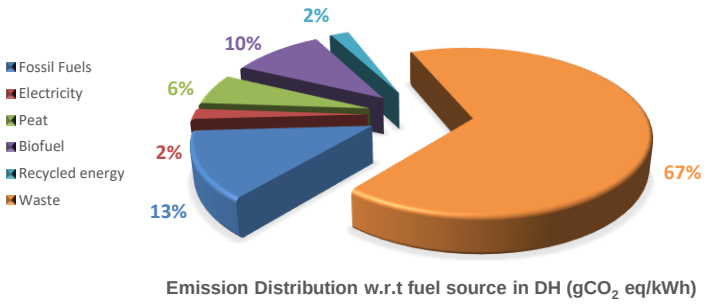

Figure 10: Distribution of CO_2 emissions among the different fuel sources that are used by contemporary DHs [47]

In Sweden, the fuel mix have changed during the last two decades as seen in Fig.11 to reach an emission low of circa **52 gCO_2 eq /kWh** (when the emissions of transport, production and energy transformation are internalized). The reduction in GHG emissions were estimated in 2020 to be one fifth those in 1990. [48]

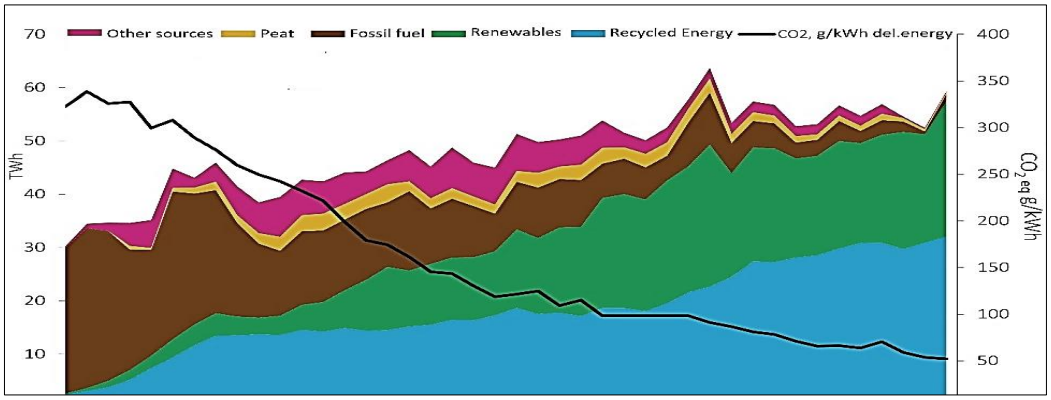

Figure 11: the energy produced by DH from 1980-2021. The increase of renewables and recycled energy sources and the corresponding decrease of fossil and Peat fuels have led to a crash in the amount of CO_2 emissions. ***Other sources:*** *electricity for heat pumps, electric boilers and auxiliary appliances.* ***Recycled energy****: flue gas condensation, waste heat, RT chips, heat from heat pumps, waste gases/residual gases and waste.[48]*

2.8 Geothermal Heat pumps

GHPs are highly efficient technology that is gaining "ground" in both commercial and residential buildings. GHPs utilizes the free energy in the ground to heat or cool buildings through heat exchange circuits i.e., it extracts heat from a source and transfers it to a sink at a higher temperature [3] [49] [50]. This is done exchanging energy between the air in the house and the energy in the ground via heat exchangers and a suitable operating medium that flows in the circuits.

There are different types of GHP:

- Ground to air: used instead of forced air central heating and cooling system
- Ground to water: used to heat water and for space heating/cooling and used in radiator within the room.

They are known for their high Coefficient of performance (COP) e.g., a COP of 4-6.5 (400-650% efficiency). COP is defined by the following equation [3] [49]:

For heating:

$$\boldsymbol{COP_{heating}} = \frac{\boldsymbol{T_H}}{\boldsymbol{T_H - T_C}} \qquad \text{Eq (3a)}$$

For Cooling:

$$\boldsymbol{COP_{cooling}} = \frac{\boldsymbol{T_C}}{\boldsymbol{T_H - T_C}} \qquad \text{Eq (3b)}$$

T_H and T_C are the thermodynamic temperatures in Kelvin of the hot and cold reservoirs respectively

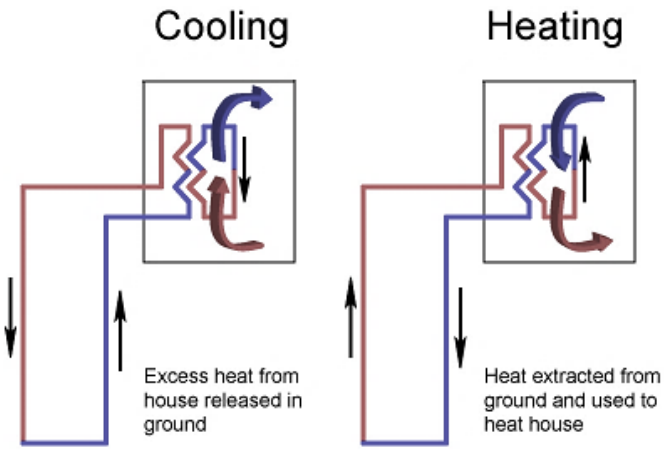

Figure 12: GHP principle. for Cooling and Heating [49]

2.9 Maximum Payback time

An investment that could pay for itself and ensure a surplus of profit is very lucrative to investors. The method of maximum payback period could follow two different pathways:

1- Undiscounted Payback time (PBT)
1- Discounted payback time (DPB)

2.9.1 PBT

The PBT is calculated for investment without discounting; the total value of the investment, sometimes referred as initial value Pinitial, is divided by the annual return, cash flow (CF), and is expressed in the following equation [2] [51]:

$$\mathbf{PBT} = \frac{P_{initial}}{CF} \qquad \text{Eq (4)}$$

2.9.2 DPB

The DPB is calculated iteratively by taking the cumulative effect of annual CF from each consecutive year on the net present value (NPV) and the discount rate (D%) into consideration [51]:

$$NPV = -P_{initial} + \sum_{k=1}^{n} \frac{CF}{(1+D\%)^k} \qquad \text{Eq (5)}$$

Initially, NPV will have a negative value (only Pinitial exists), then CFs are accumulated until the term NPV changes from negative to positive. If NPV_{t-1} is the last negative term and NPV_t is the first positive term then DPB can be calculated according to the following expression [52]:

$$\mathbf{DPB} = (t-1) + \frac{|(NPV_{t-1})|}{(NPV_t - NPV_{t-1})} \qquad \text{Eq (6)}$$

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3 Method

The building in question is a multistorey office building situated in Gävle Fig.13 was investigated in this study to evaluate which parameter or set of parameters that could possibly generate energy savings i.e., energy performance without compromising the comfort of its occupants. The reason BEP was in focus is because energy savings could lead to a reduction in GHG emissions. The results of applied parameters will be compared against each other according to three fundaments:

1- Energy savings
2- Thermal Comfort
3- Carbon Dioxide emissions (GHG in general)
4- Economic Feasibility

The parametric evaluation was built on several types of factors that are mentioned below:

A. Geographical Location and climate:
    a. Gävle, Sweden
    b. Sapporo, Japan
    c. Beirut, Lebanon
    d. Jakarta, Indonesia
B. Building orientation
    a. 90^{0} clockwise
C. Shading
    a. Internal shading
    b. External Shading
D. Alternative Energy Supply
    a. GHP with a COP = 4.0

Figure 13:Rådhuset in Gävle: Northern façade [16]

3.1 The Software

The evaluation was run in a building performance simulation software or BPS software known as Indoor Climate and Energy or IDA ICE version 4.8. It is a dynamic simulation software developed by EQUA that supports multiple zones to simulate thermal comfort and evaluate energy loads and usage. The simulation can be done on a room level or for the entire building. The software was validated according to CEN standards EN 15255-2007, 15265-2007 and 13791, as well as ASHRAE Standard 140-2004 [6] [52]. This software has also been used in other studies to evaluate building energy system and thermal comfort [53].

3.2 The setup

The Base model (Fig. 14) in Gävle, which was validated in the previous study [2], was simulated pre and post the application of LEF using the forementioned chosen parameters (in tables and figures below). This was done to generate an understanding of how the building would perform (EnU and TC) at each of the proposed parameters before and after the application of LEFs. Moghaddam found out that it was not economically feasible to invest in LEFs in Sweden under the current energy prices of 2018, but also not to forget their positive impact on both the environment (reduced EnU) and the thermal comfort:

> *"However, the relatively high price of the films and low price of district heating combine to result in a rather long payback period of around 30 years. Thus, the films seem scarcely attractive from a pure economical viewpoint, but their use may be warranted for energy/environmental and thermal comfort reasons" [2]*

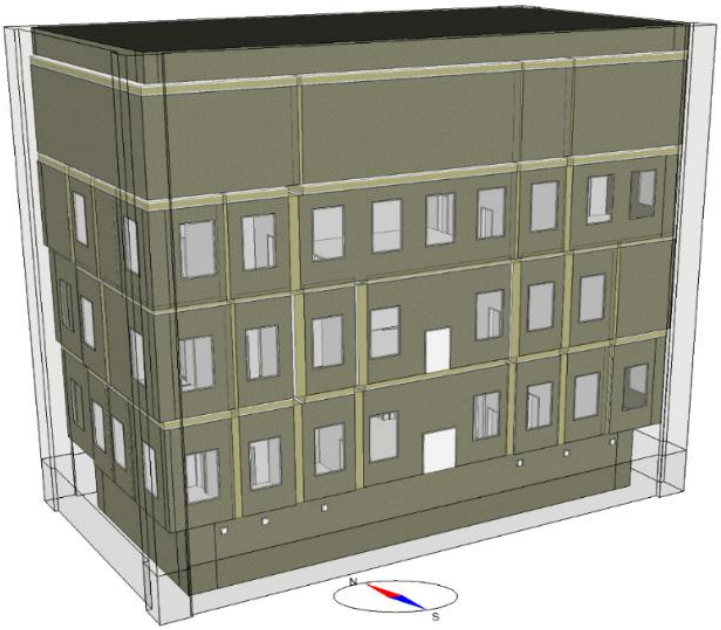

Figure 14: The IDA-ICE model that was used in the parametric study

The proposed parameters gave rise to various hypothetical scenarios where the building was modelled at other locations, different orientations and in scenarios using internal and external shadings as accessories to mitigate SHGs. The detailed data concerning the building envelope that were used in the model are in the Tab.2, while the data about the envelope's thermal bridges in appendix B Fig.1.

Table 2: Envelope specifications used in the model throughout the parametric study.

Envelope	U-Value (W/m^2.K)	Thickness (m)
External Wall	0.8134	0.62
Internal walls	1.157	0.404
Internal Floors	0.3688	0.365
Roof	0.234	0.515
External Floor	2.9	0.255
Basement towards ground	3.333	0.21
Slab towards ground	2.9	0.255

Data in Tab.2 were unaltered to ensure a degree of comparability with the parent model in the previous study. The main changes in the envelope were in the form of U- and g-value as seen in Tab.3 that was done in order to understand the effects of SHGs on the magnitude of delivered energy.

3.3 The Building Specs

The total number of windows was 71 panes divided: North (29), South (24), East (9) and West (9). The type of LEF used in the study was CC75 Low-E (3M) from Thinsulate with 15 years guarantee [2].

Table 3: Glazing parameters and specifications: T_{vis}: Visible transmittance, T_{str}: Solar transmittance.

Glazing	U-Value (W/m^2.K)	g-Value	T_{vis}	T_{str}
2-pane 4-12-4 (3-30-3 mm)	2.5	0.76	0.81	0.7
With LEF	1.55	0.51	0.66	0.5

The main entrance of the building is shown in Fig 13, i.e., the northern façade, was modelled to have the highest number of windows which according to research is the side that receives the least SHG in the northern hemisphere (NH). Depending on the location of the building it could have either elevated heating energy use in cold countries of the NH or a reduced energy levels in the southern hemisphere (SH) (see Fig.15)

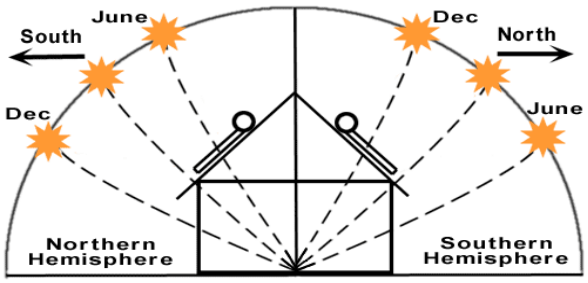

Figure 15: A comparison between the solar angles during the seasons in both global hemispheres [54]

3.4 Internal gains and Losses

The building has the following components of internal gains (see Tab.4) the occupants followed a daily work schedule from 06-18 only during weekdays otherwise the building was in a dormant state.

Table 4: A list of the internal gains within the envelope excluding the solar effect.

Internal Gain	Total	W
Occupants	59	90
Lights	450	24
Equipment	59	125

The same schedule was applied to the operation of lighting and equipment See Fig.16.

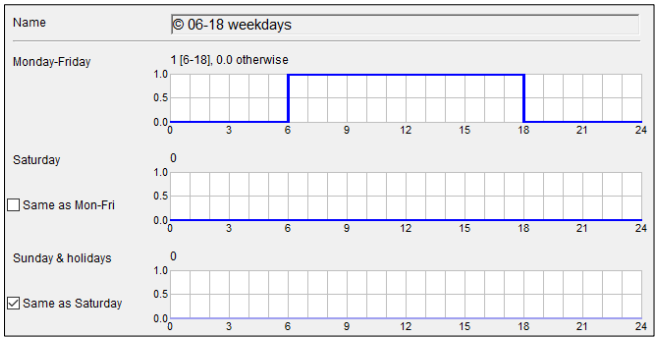

Figure 16: occupancy schedule that governed the Internal gains in Tab.4

The building model was created in study [2] with the original parameters as in Fig.17. The air handling unit was a constant air volume system (CAV) with supply and return air flow of 1.3 L/s.m^2

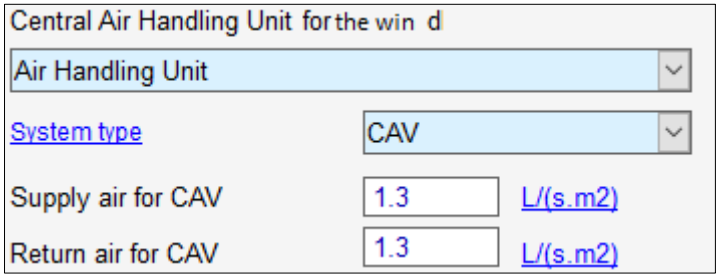

Figure 17: Specifications of the central AHU in the model.

The need for space heating and domestic water are fuel based and share a COP of 0.9. The electric cooling is supplied by an electric heat pump of COP 3. In the last simulation an electric heat pump of COP 4 will be used to supply the heating demand of the building. this will resemble a geothermal heat pump (see Fig.18).

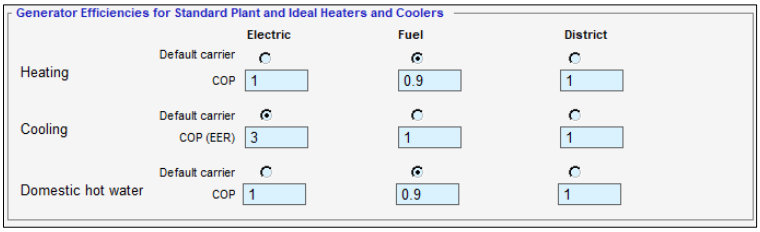

Figure 18: The Efficiencies and energy carriers of the plant and ideal Heater/cooler.

The indoor temperature was adjusted between a heating set-point of 21°C and a cooling set-point of 23°C. the infiltration was chosen to be according to the Wind driven flow with an air tightness of 0.84 L/s.m^2 at a pressure difference of 50 Pa as shown in Fig.19

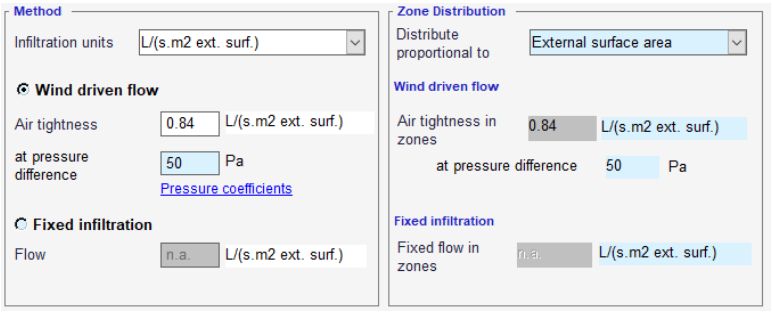

Figure 19: Data of the infiltration values in all the models.

Extra Energy delivered and heat losses are visible in Fig.20. The facility has an average hot water use of 2 kWh/m²•yr. Distribution system losses are those lost by the bought energy under distribution in the building.

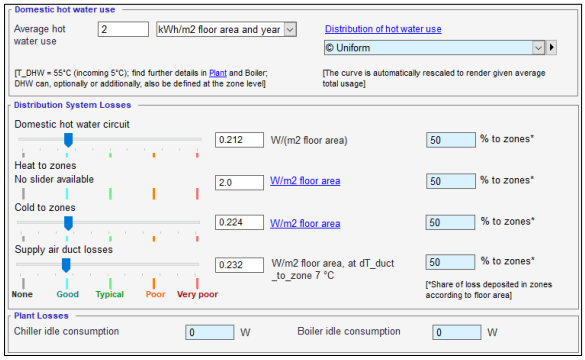

Figure 20: Distribution system losses in the model in W/m²

3.5 Thermal comfort

PPD was the main indicator of thermal comfort in this study. It was also used to generate a term of satisfaction per delivered energy index expressed as (1-PPD) per kWh/m²•yr. This was one of the assessment tools of the building.

The software created Energy/comfort reports (requested by the user) at the end of each run in which the % of dissatisfaction were presented (see Chapter 4 for details).

3.6 Influencing parameters

3.6.1 Location

The location, as described in the introduction, varies with respect to the solar angles during the year. It is noticeable how the solar seasonal position changes from one country to the other as see in Fig.21. A direct observation could be made when examining Fig.21 was that Gävle had the lowest solar elevation angles in both winter and summer.

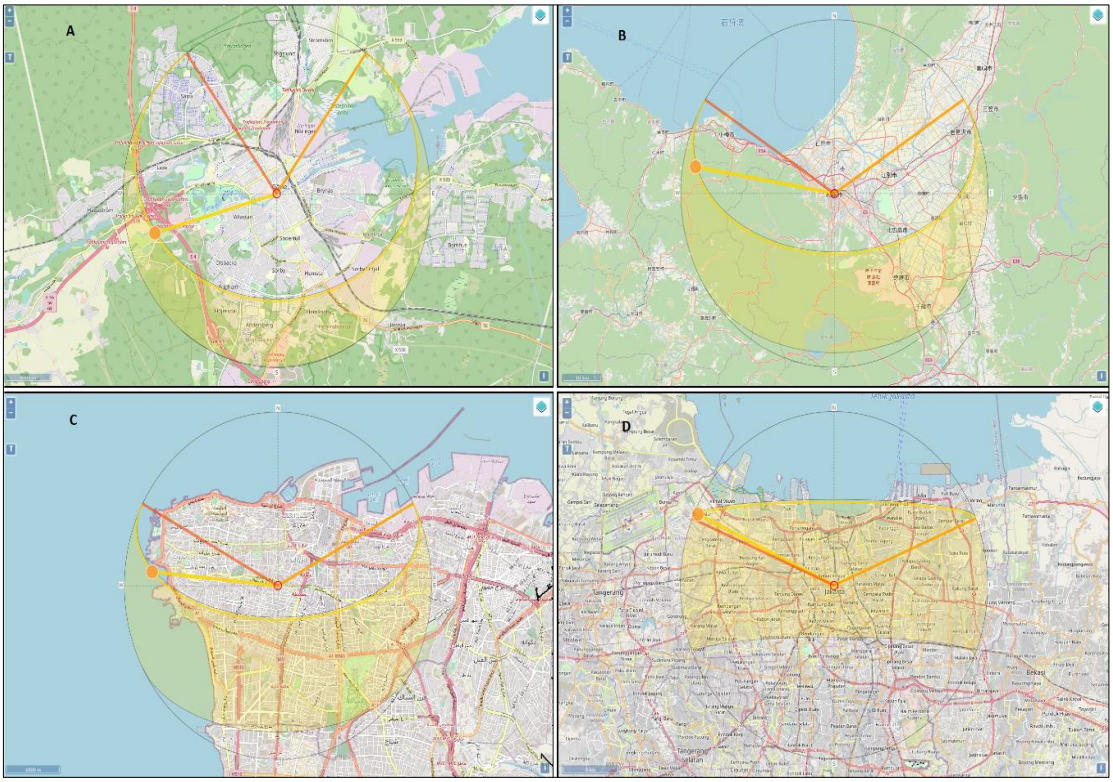

Figure 21: Solar Angles at (A) Gävle, (B) Sapporo, (C) Beirut and (D) Jakarta. [55]

The locations were varied using the database of the software that included a plethora of location properties that affect energy transfer through the structure as well as the level of thermal comfort. Tab.5 gives a reference to the used data files.

Table 5: location of cities, Climate classifications (refer to Fig.6), Weather file sources and the Data files extracted from IDA-ICE database.

Location	**Coordinates**	**Climate (M, P, T)**	**Weather source in IDA-ICE**	**Data files**
Gävle Sweden	60.6749° N, 17.1413° E	Dfc (Snow, F. humidity, C. Summer)	SMHI Sveby, SMHI Klimatfiler	
Sapporo Japan	43.0618° N 141.3545° E	Dfb (Snow, F. Humidity, W. Summer)	ASHRAE IWEC2 Weather File for SAPPORO.	Data from ASHRAE Fundamentals 2013
Beirut Lebanon	33.8938° N 35.5018° E	Csa (Warm temperature, Dry warm summer)	ASHRAE IWEC2 Weather File for BEYROUTH-AP.	
Jakarta Indonesia	6.2088° S 106.8456° E	Af-Am (Equatorial, F. humid/Monsoonal)	ASHRAE IWEC2 Weather File for JAKARTA-SOEKARNO-HA.	

3.6.2 Orientation

The orientation of the model was rotated 90° clockwise as seen in Fig.22. all the other parameters of the Base model are kept the same. The south and north façades (24 and 29 windows) became the west and east respectively. It should supposedly cause an increase in the delivered energy for heating due to loss of SHGs

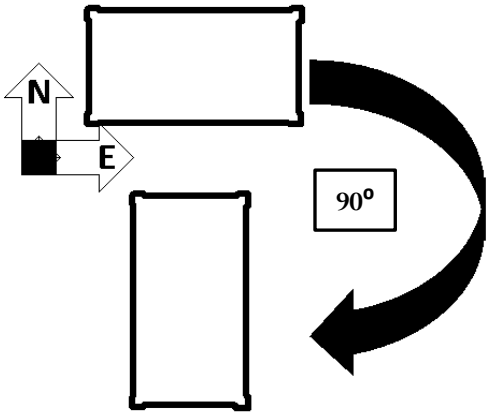

Figure 22: The 90° clockwise orientation of the building of scenarios B1 and L1 (see Tab.6)

3.6.3 Shading

One way to diminish the energy gain by solar radiation is to block and/or diminish the intensity of the incident solar radiation by shading. Anything that obstructs and/or attenuate the influx of solar radiation should result in reduced solar gains in the form of heat (see Fig23). Two types were used namely internal and external shading.

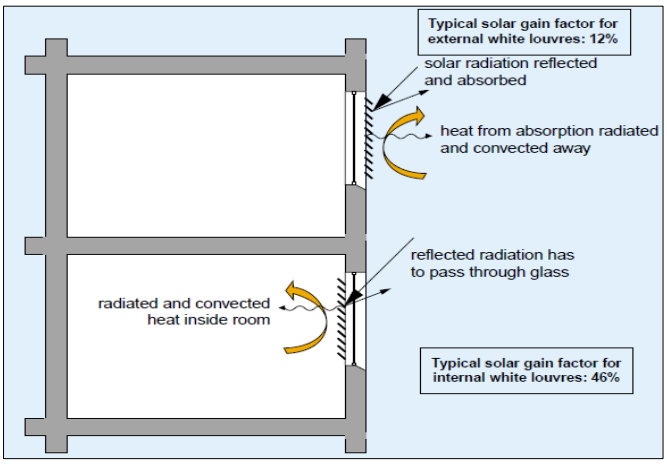

Figure 23: Internal versus External shading: influence on SHGs, transmitted, reflected and absorbed solar radiation [35].

3.6.3.1 Internal Shading

The type of IS chosen for the purpose of this study was light colored and lightly woven curtains. The motivation was that some sunlight should penetrate the room and allow part of the SHGs in the original model to be generated and contribute to reduction in the heating load especially in Gävle. At the same time dark curtains would generate too much heat in warmer countries and increase the cooling load the Fig.24. [26]

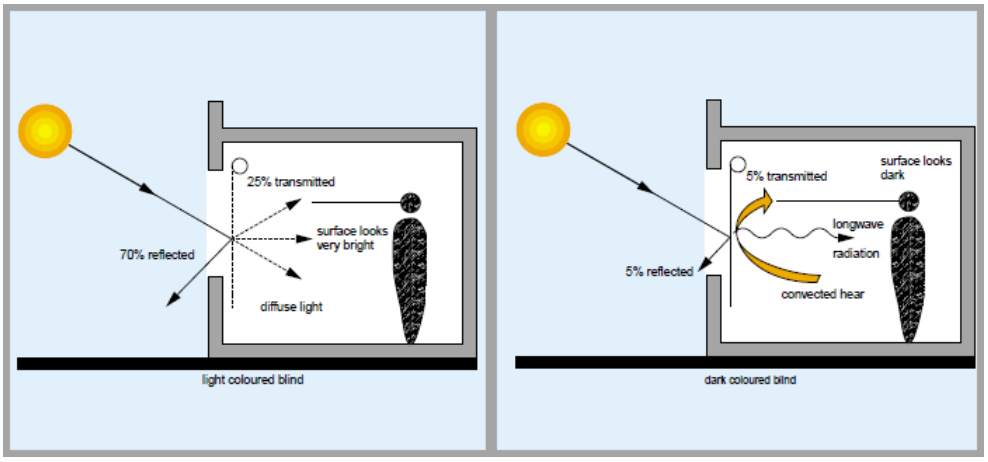

Figure 24: The difference in solar gains between dark and light curtains [35].

The curtain parameters that were used function as multipliers to the original data in Tab.3 and are displayed in Fig.25. Only one type of curtains was used in this study.

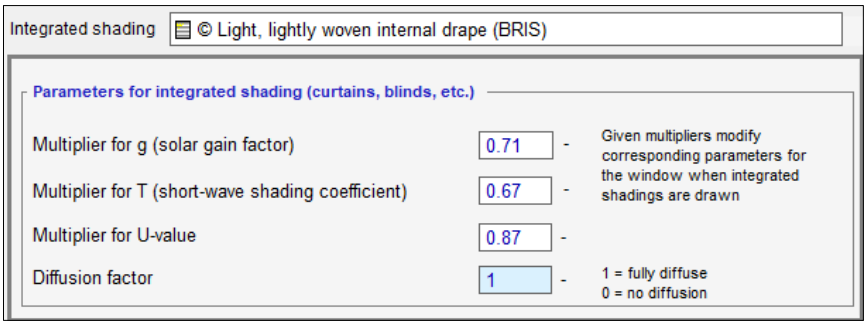

Figure 25: The details of lightly woven curtains used in the study

3.6.3.2 External Shading

That was done in disregard to the prohibition the building has on outside alterations to the façade and only for the sake of accumulating more information about the building. In theory it should decrease the SHGs and an increase in the heating load in colder locations, namely Gävle.

The ES in that were used in this model were of two modes (Fig.26):

a- Controlled by temperature when the outside air temperature would reach 25°C. The purpose of this control limit is to simulate an automatic setpoint for the awnings to be lowered. This was an attempt to prevent the room temperatures from rising above 27°C.
b- Controlled by the sun i.e., they are drawn when the Sun angle is less than 90°.

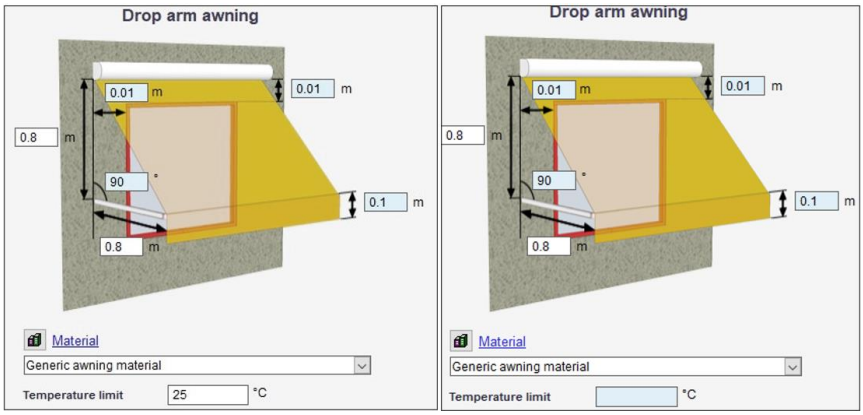

Figure 26: External shading; Left: Tout controlled. Right: Sun controlled IDA ICE.

The models and their respective parametric configurations are designate a letter and a number suggesting a parametric simulation pre-LEF and post-LEF (Tab.6). All energies are given in energy per floor area and year (annum) i.e., kWh/m²•yr unless stated otherwise.

Table 6: Case nomenclature for B-, L- and C cases

Model Pre-LEF	Model Post LEF	Models with GHP
B0: Base model (BM)	L0: B0 +LEF	CB0: GHP + B0
B1: (BM) + 90° clockwise orientation	L1: B1 + LEF	CL0: GHP + L0
B2: BM+IS	L2: B2 + LEF	
B3: BM + ES + shading control (Tout)	L3: B3 + LEF	
B4: BM + ES without shading control	L4: B4 + LEF	

The simulation is divided into:

1- B-cases: Base model B0 and all the forementioned parameters
2- L-Cases: LEF model L0 with the same parameters
3- C-cases: GHP with B0 and L0 only.

The strategy is to examine:

1- if the proposed parameters could replace the benefits that LEF has resulted in (L0 and [2])
2- If the combination of LEF and one or more of the parameters would synergize and reduce the energy used more than L0 did in [2]
3- Assess the economic value of the LEF after the inflation rates and energy prices of 2022
4- Extra test with an electric heat pump of COP 4.0 and an economic feasibility test.

3.7 Alternative energy supply

The introduction of a GHP energy source of heating to replace the fuel driven DH. Domestic hot water remained to be from the DH, while fuel driven (COP: 0.9) was replaced by an electric GHP with a COP of 4. The benefits in this area should reduce the energy bill while maintaining an acceptable thermal comfort in the building. The economic feasibility was investigated at a fictious warranty time that matched the LEF's [2] of 15 years guarantee.

3.8 The price of electricity

The prices of district heating and energy in Sweden was checked [46] and it was found that in general prices have risen during 2022 to around an average price of 0.08-0.09 €/kWh taking all district heating production in Sweden into consideration. The price for electricity has also increased to around 0.125 €/kWh and was forecasted to reach 0.3 €/kWh at the end of 2022.

The prices displayed in Appendix C Tab.1 [56] are a comparison of the same day and month but one year apart (1st of July 2022 versus 2021) the price comparison (in €/kWh) shows an alarming trend: a quadruple increase in energy prices which could be because of the current situation in Europe since Feb 2022. The pricing in this study, however, was decided to be between 0.08-0.12 €/kWh to avoid the current volatile process of energy which could change at the end of 2022.

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4 Results

The results followed the methodology described in Chapter 3 and at the beginning of this section. The subtitles start with a general description of what to expect before the display of results.

The model in [2] was subjected to a parametric study that examined the effects of location, orientation, internal and external shadings as well a GHP installation.

The results of all the cases will be presented with respect to TDE, SHGs, TC, CO_2 emissions, economic viability and a comparison of the best possible scenarios. The discussion of which will be conducted in Chapter 5.

4.1 B-Cases

This part displays the results of the parametric simulations. The B-cases were run through the simulation, their numbers processed to create the figures and tables.

4.1.1 TDE

To understand the EnU of the building at the ground state i.e., B0 the simulation was run to reproduce the same results as [2]. The EnU was aggregated into three parts:

- Electric Usage: Lighting, aux HVAC, appliances
- Heating Need: space heating and domestic hot water from DH (with **52 gCO2 eq/kWh**)
- Cooling Need: Electric Cooling

It was found that some EnUs were nearly identical for all the scenarios such as lighting, domestic hot water and appliances (see Tab.1 in Appendix A for more details)

As Seen in Fig.27 the majority of EnU was invested to satisfy the heating needs of the building; it was found that the heating demand was circa **150.3 kWh/m²•yr** which is equivalent to **7.8 kg CO_2 per year**. The rest are composed of electric usage and appliances (see appendix for details).

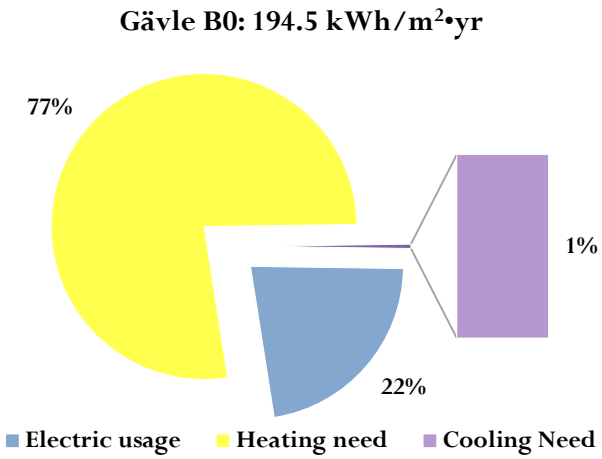

Figure 27: The majority of EnU in Gävle is consumed for space heating and domestic hot water use.

The next result is when the parameters were applied to B0 the different energy values are seen in Fig.28.

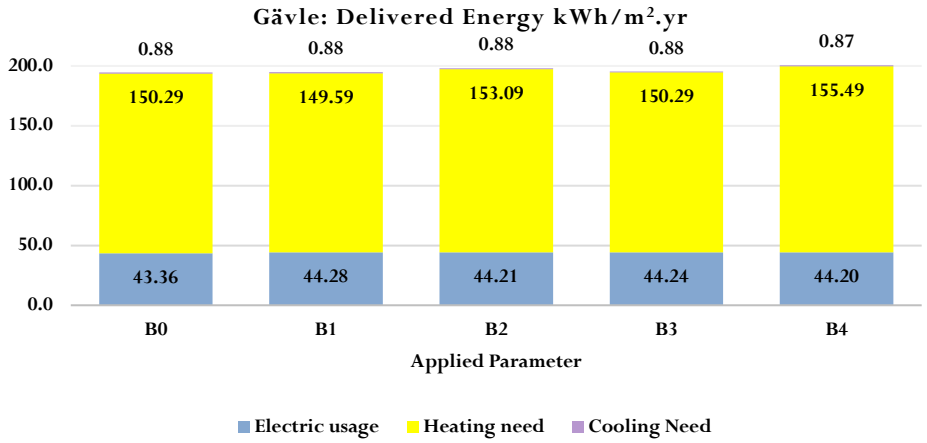

Figure 28: Gävle Delivered Energy Profile under the influence of the other parameters excluding Location.

The delivered energy figure is the lowest is the B1 configuration with an average electric usage and a relatively low Heating need of 149.6 kWh/m²•yr. The highest EnU is scenario B4 circa 200 kWh/m²•yr.

When B0 was simulated at the different geographical locations the climate° induced a tradeoff between heating needs and Cooling needs as the B0 travels from northern Europe towards the equator (Fig.29).

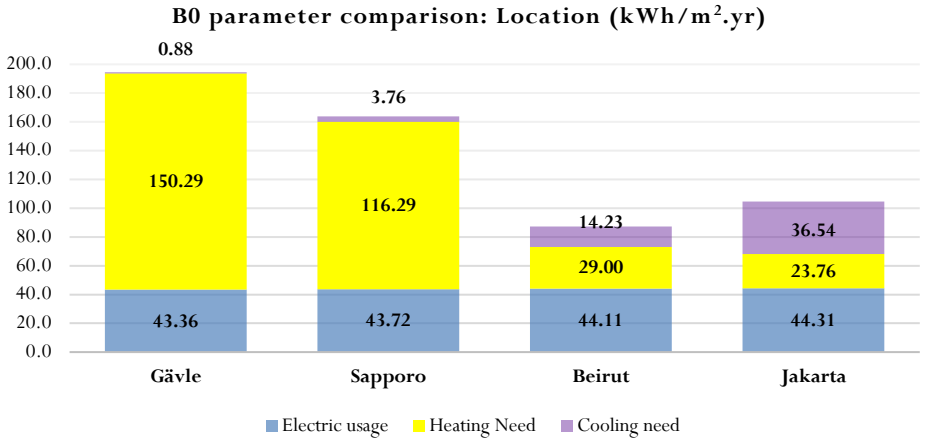

Figure 29: A chart of comparison between the energy consumption of B0 at the different locations

Gävle has the highest energy consumption according to this model and this simulation because there was no active cooling in the warmer locations except for electric cooling.

4.1.2 SHGs

The results of the heat gains for the building in B-case configurations. The B1 configuration has the highest SHGs (see Fig.30).

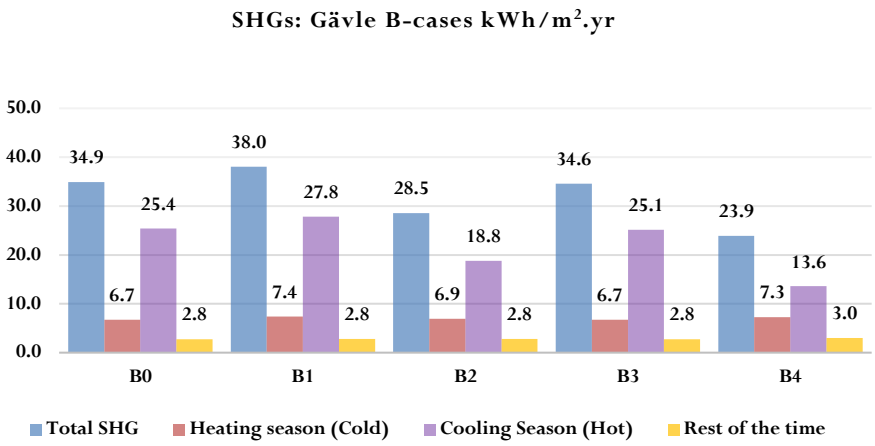

Figure 30: SHGs at Gävle under the influence of the different parameters. Magnitude of energy gained by the solar radiation is in this order: B1>B0>B3>B2>B4.

The heat · gained during the cold season was around **7.4 kWh/m²•yr** which could be useful to decrease the need for heating during that time while B4 takes the last place in SHGs, but is has a similar heat gain during the cold season **7.3 kWh/m²•yr**, but more on that in section 6. The "rest of the time" SHGs are the times in between the heating and cooling season designated by the software.

Fig.31 displays the regional effect on SHGs depending on the suns position at that location during the different seasons. B0 Jakarta has SHGs that tops the chart due to its equatorial location that receives relatively higher dose of solar radiation per year.

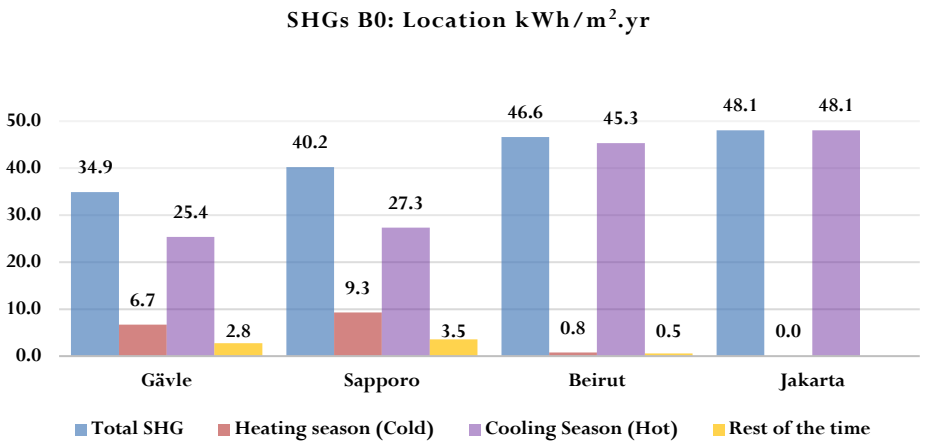

Figure 31: SHGs with respect to B0 at different Locations. The effect of the climate is evident as warmer climates have a milder heating season with the exception of Jakarta that lacks such a season.

4.1.3 TC

Fig.32 reveals the results of how comfortable the occupants feel in their dwellings. The configuration B4 has the best percentages that indicated a better TC than the rest. It is a **36%** reduction in PPD the number o

f hours when the occupants are dissatisfied compared to B0.

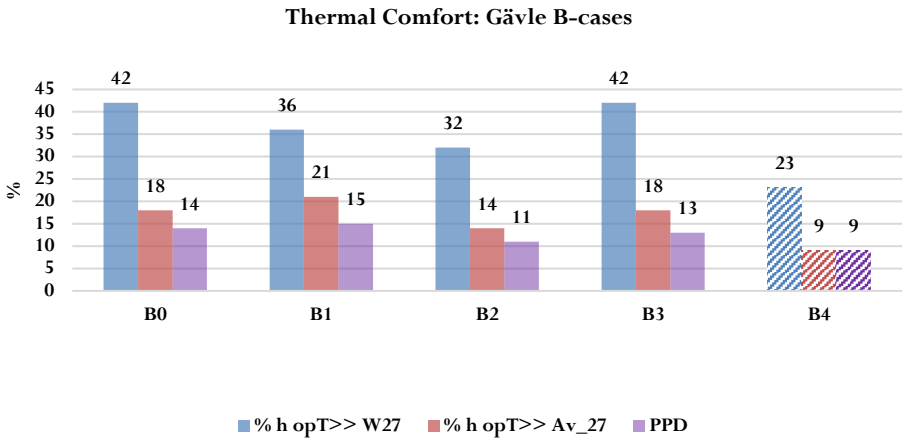

Figure 32: Thermal comfort main indicators. The percentage of hours in worst and average zone that have an operating temperature higher than 27 C (W27 and Av_27 respectively) along with the PPD index of dissatisfaction.

IDA-ICE gave recommendations of the best configuration with respect to comfort per energy indicators at the end of each simulation. Fig.33 displays a comparison between the B-cases with respect to comfort in **kWh/m²•yr**. If the PPD was the percentage of total occupant hours with thermal dissatisfaction then (1-PPD) is the percentage of total occupant hours with thermal satisfaction. This was then divided by the energy per floor area e.g., the higher the number the more comfortable the dwelling is; therefore we have a tool to choose a win-win configuration.

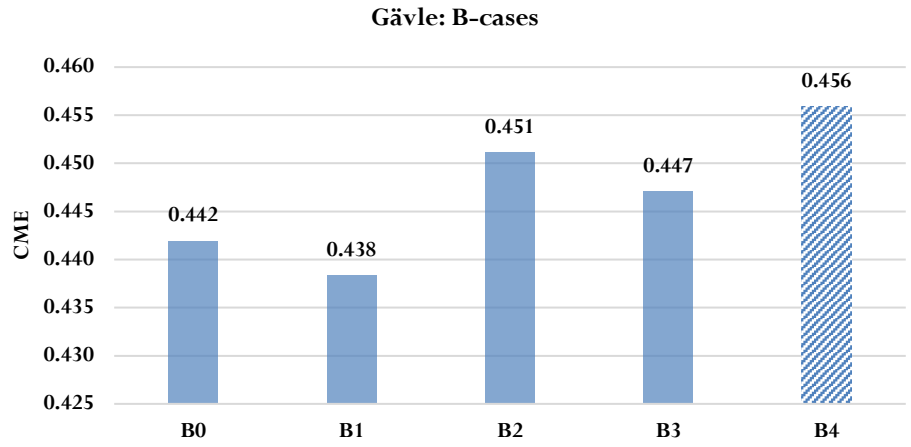

Figure 33: Comfort per energy per area for all the parameters in Gävle.

Configuration B4 has the best comfort per delivered energy per floor area. PPD of B4 was found to be 9% see also Fig.32 this means that the occupants are satisfied 91% of the time with a EnU of 199.7 kWh/m²•yr.

4.2 L-Cases

The same procedure as the previous section, but with the application of LEF. The following results of the L-cases will be a matter of discussion and comparison with the B-cases.

4.2.1 TDE

The results in the following figure seem to be similar in comparison to Fig.27. The similar distribution of energy usage in Fig.34 is of a reduced energy magnitude by 4.6 % to be precise.

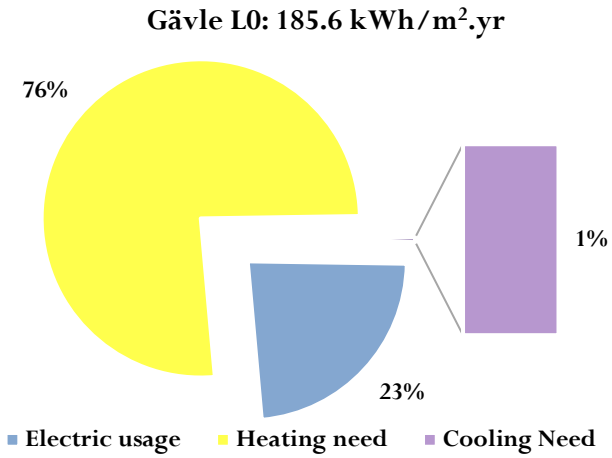

Figure 34: The majority of EnU in Gävle is still consumed for space heating and domestic hot water use. This is to be expected given the climate type of Gävle.

The same configuration is run through the different parameters to produce the results in Fig.35. Configuration L1 had a total of 185 kWh/m²•yr i.e., a 4.9 % reduction, L3 was identical to L0 while the other parameters lead to a higher energy consumption than L0: L2 and L4. The detailed results can be found in Tab2. Appendix A.

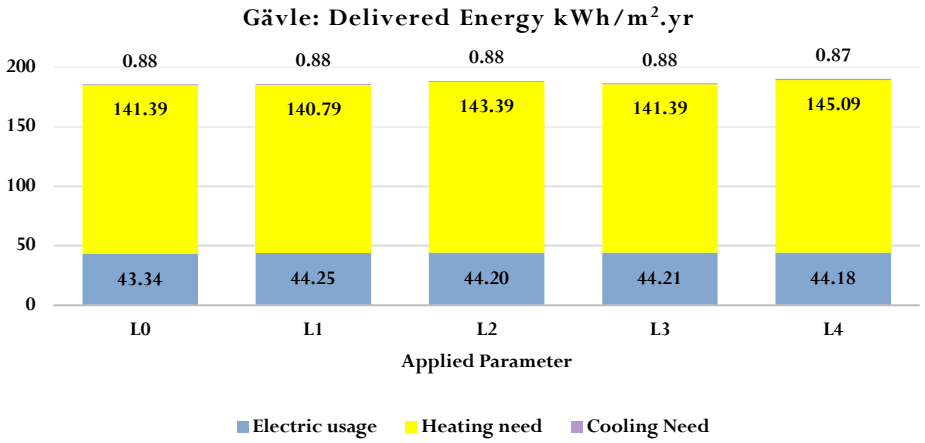

Figure 35: parametric simulation of the different local parameters in Gävle. L1 has the lowest metered energy.

The following chart (Fig.36) shows a comparison in delivered energy of L0 configuration at the different geographical locations.

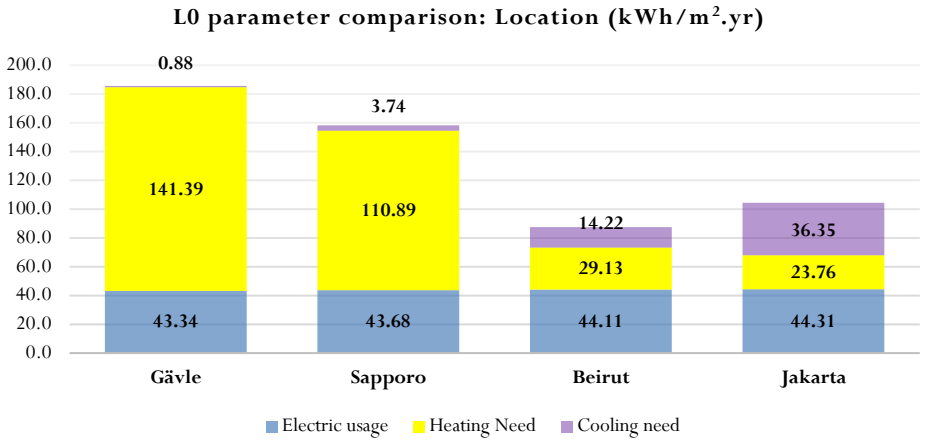

Figure 36: The building configuration includes a heater; colder locations use most of the energy for space heating. The neeed for "cooling" is relevant in the warmer locations.

The differences between B-cases (Fig.29) and L-cases in terms of location were a reduction in delivered energy of about 5% in Gävle, ca 4 % in Sapporo, 0% in Beirut and Jakarta.

4.2.2 SHGs

There was a reduction in SHGs for all the L-cases after the application of LEF as seen in Fig.37. LEF have effectively reduced the intensity of incident solar radiation into the building.

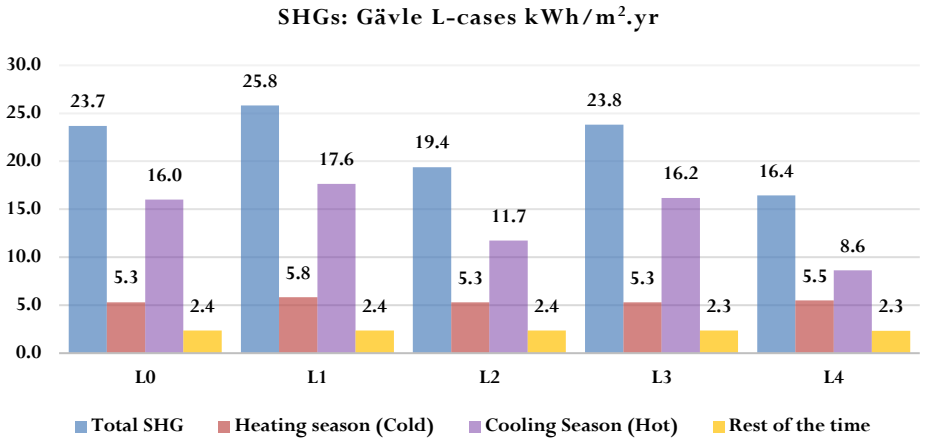

Figure 37: a varied result between the applied parameters in Gävle. L4 has the lowest total SHGs due to the sun controlled awnings.

The average reduction in the total SHGs between the corresponding B- and L-cases was found to be a 32% reduction. A closer look revealed an average reduction of 22% in SHGs during the cold season and an average of 37% reduction of SHGs during the warm/hot season.

The same reduction in SHGs with respect to location (Fig.38) was found after data processing with the exception of a 32% for Beirut and Jakarta during the hot season. More details are found in Appendix B SHGs.

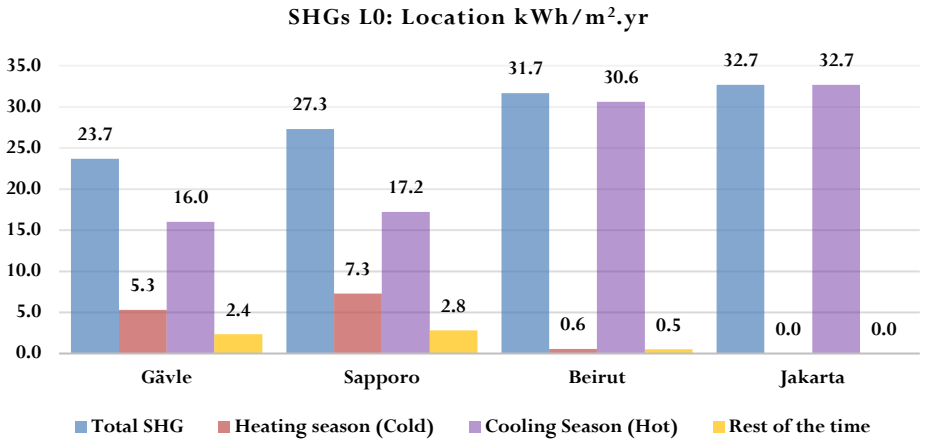

Figure 38: comparison of SHGs with LEF per geographical location. Warmer countries practically have no cooling season in comparison with Gävle and Sapporo

4.2.3 TC

Fig.39 displays a reduced level of dissatisfaction in the TC factors. L0 had a 21.5% improvement in the PPD index in comparison with B0.

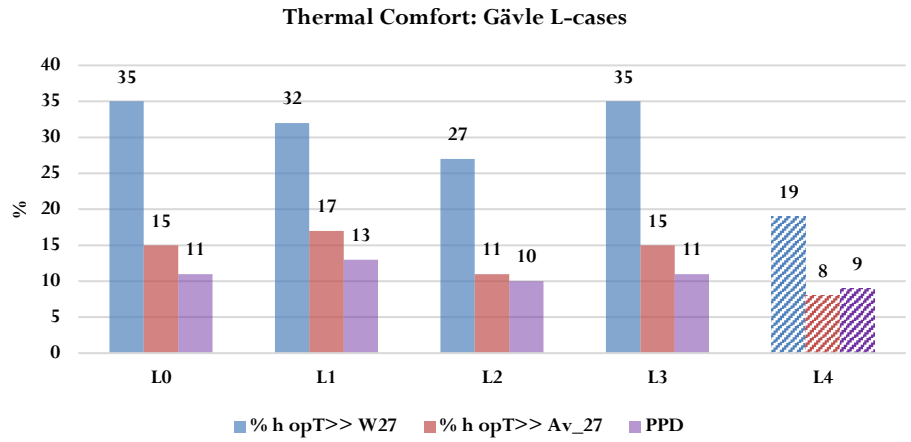

Figure 39: TC indicators showing a decrease in the dissatisfactory factors (W27, Av_27 and PPD) due to the use of LEF.

In Fig.40 the resultants showed an improvement in the comfort per metered energy (CME) index. The result compared to the previous B-case show a positive development such that the lowest L-case (L1) > highest B-case (B4). The percentage of thermal comfort augmentation from B to L cases is an average of 7% (9-5%) increase.

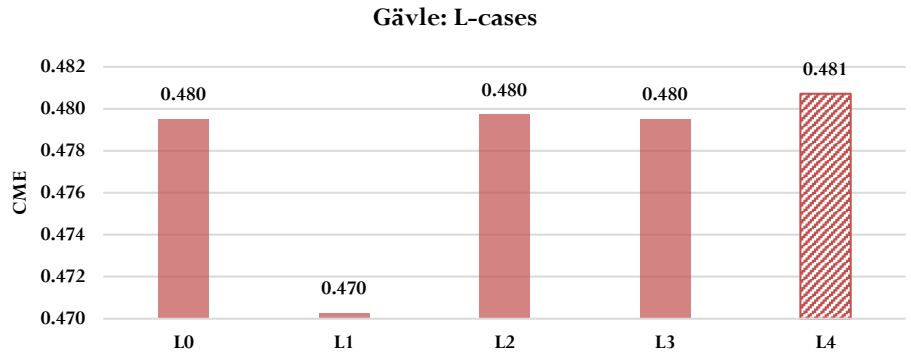

Figure 40: Comfort per energy per area for all the parameters in Gävle with LEF

It has to be noted that such a comparison makes more sense when it is the same building model, i.e., building specific, that is undergoing a parametric evaluation.

4.3 Thermal Comfort in other Locations: Best possible scenario

The details of this figure are in Appendix C Tab.2. All locations have undergone the same simulation. It was found after processing all the data that the parameters in Fig.41 are a location specific best fit scenario (recommended by the software).

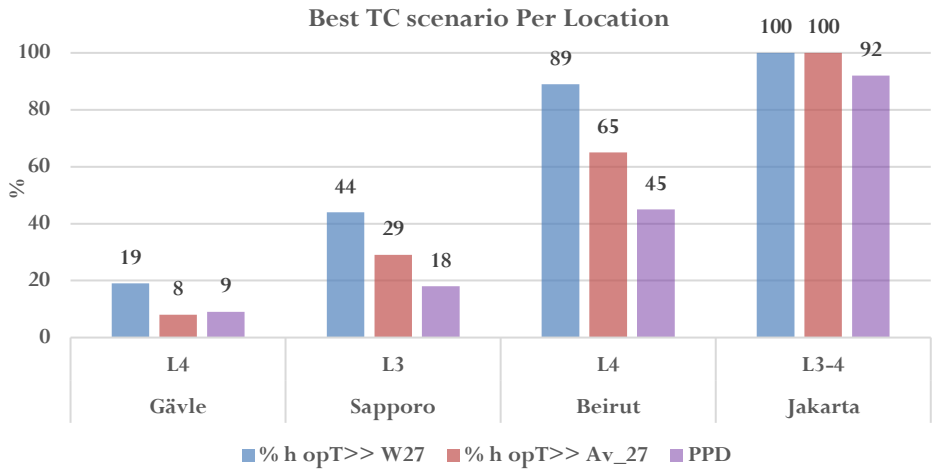

Figure 41: A comparison between the best thermal comfort and applied parameter(s) per location

4.4 Carbon Dioxide emissions

The models are compared with respect to the carbon dioxide emissions difference with B0, 52 gCO2 eq/kWh/yr., the product of the carbon rate with the difference in energy between the models yields the results in Fig.42.

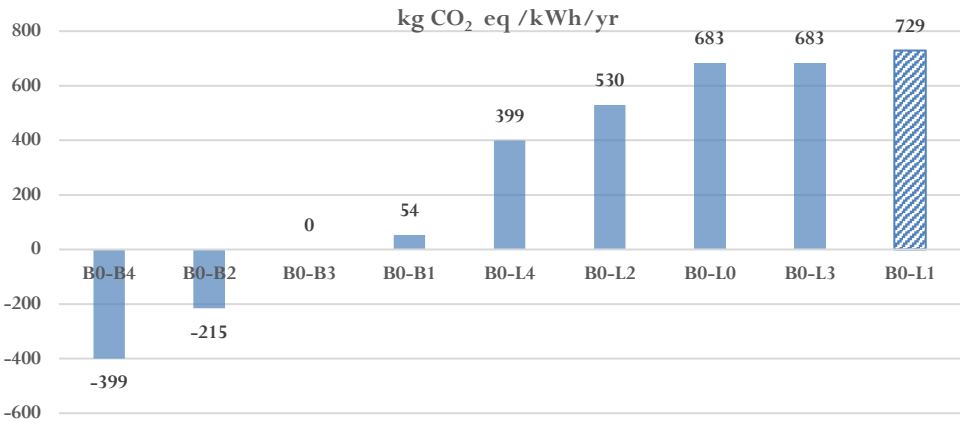

Figure 42: CO_2 emission: the difference between B0 and the other parameters. Positive difference mean reduction of CO_2 and vice versa.

4.5 Alternative Energy Supply

4.5.1 Geothermal Heat Pump

The results of the GHP have been compiled into the compound figure below (Fig.43). The combination of LEF and a GHP generated the best results in every category.

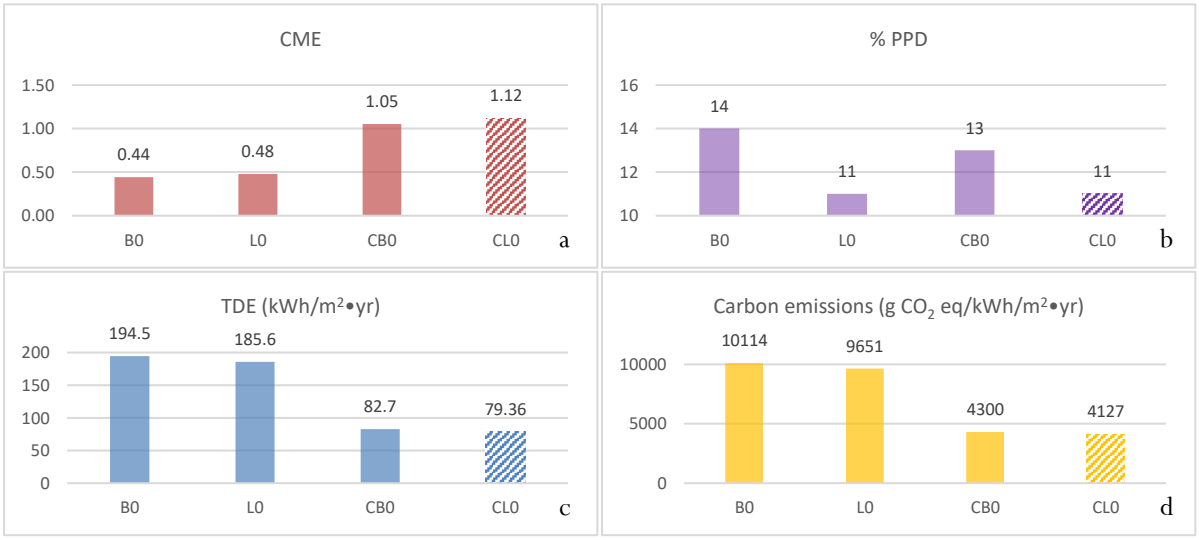

Figure 43:The collective results B0, L0 and the C-cases. (a) displays the CME index; (b) is the general PPD rating; (c) the TDE for each scenario; (d) is the CO_2 emissions of each of the chosen cases.

The CL0 configuration had the best results though some results are remarkably close to CB0. Both ·C-cases had the highest EnU reduction (Fig.43a) which is equivalent to decrease in the emissions of GHGs such as CO_2 (Fig.43d). Both L0 and CL0 scenarios had the same thermal comfort PPD level of 11% (as in [2]). The CME was the highest in CB0 and CL0 which is logical since they both have comparable PPD and TDE.

4.6 Economic Feasibility

4.6.1 Investment in LEF

The payback period in [2] (LEF would cost 152 €/m² in total 25 k€) showed around 30 years which was beyond the product warranty (15 years) that would still be true if the price of a delivered kWh was still around 0.07-0.08 €/kWh. The recent pricing in Sweden was an average of 0.12 €/kWh [41] [42] [49] which makes the PBT around 16 years (Fig.44).

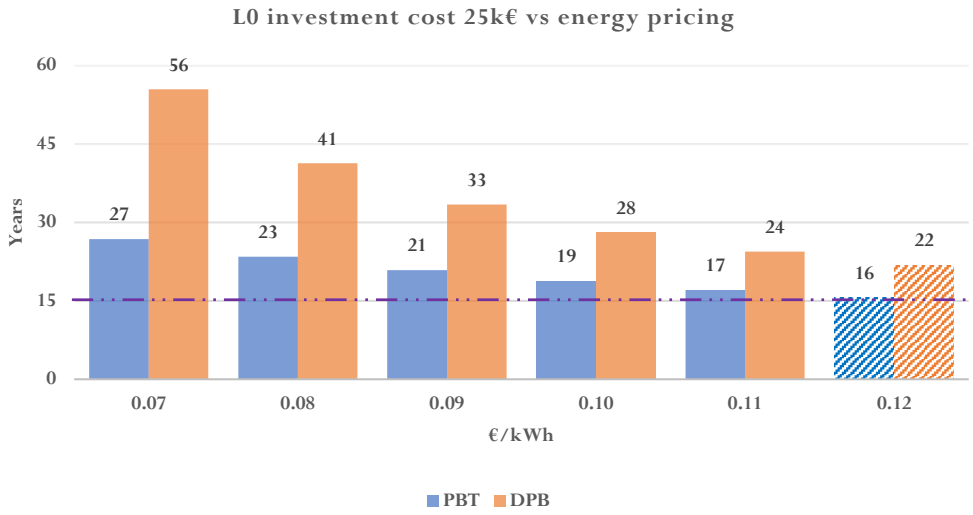

Figure 44: The different pay cack time: PBT and DPB (D%= 3%) of the Low-E investment.

The same investment but discounted payback time with internal rate of return (D% = 3%) while considering energy savings as cash flow payments, then it would take around 22 years to pay off the investment. In some research the D% used is 5% which would result a DPB of 31 years.

4.6.2 C-cases

The energy savings of CB0 and CL0 with B0 amounted to 165.1 and 170 MWh/yr. respectively. These savings were transformed into monetary savings (Tab.7) that would consequently be used as cash flows (CF)s in the PBT and DPB analysis.

Table 7: the energy prices per kWh and the corresponding energy savings in euro.

Energy Price (€/kWh)	**CB0**		**CL0**	
0.07	€	11,556	€	11,901
0.08	€	13,206	€	13,601
0.09	€	14,857	€	15,301
0.1	€	16,508	€	17,001
0.11	€	18,159	€	18,701
0.12	€	19,810	€	20,401
0.13	€	21,461	€	22,101
0.14	€	23,111	€	23,802
0.15	€	24,762	€	25,502
0.16	€	26,413	€	27,202
0.17	€	28,064	€	28,902
0.18	€	29,715	€	30,602

The energy savings of GHP (CB0 and CL0) were more than ten times the value of L0. If the total price of a premium GHP unite(s) with a COP of 4.0 to cover the heating load of the building (capacity of 70 kW) was about 60 k€ with installation and maintenance for 15 years about 20 k€ then the total price becomes 80 k€ for CB0 configuration, while for CL0 the price of L0 (25 k€) was added to result with a total of 105 k€.

The Table above shows an extended energy price range for pedagogic purposes. The PBT and DPB for both CB0 and CL0 were calculated in Fig.45 with three different D% of 3, 8 and 11%. The investment of a GHP of CB0 would barely make it through the 15 years mark at D% of 11%.

The CL0 scenario had longer PBT and DPB at the beginning, but then it became relatively close as the energy price started rising.

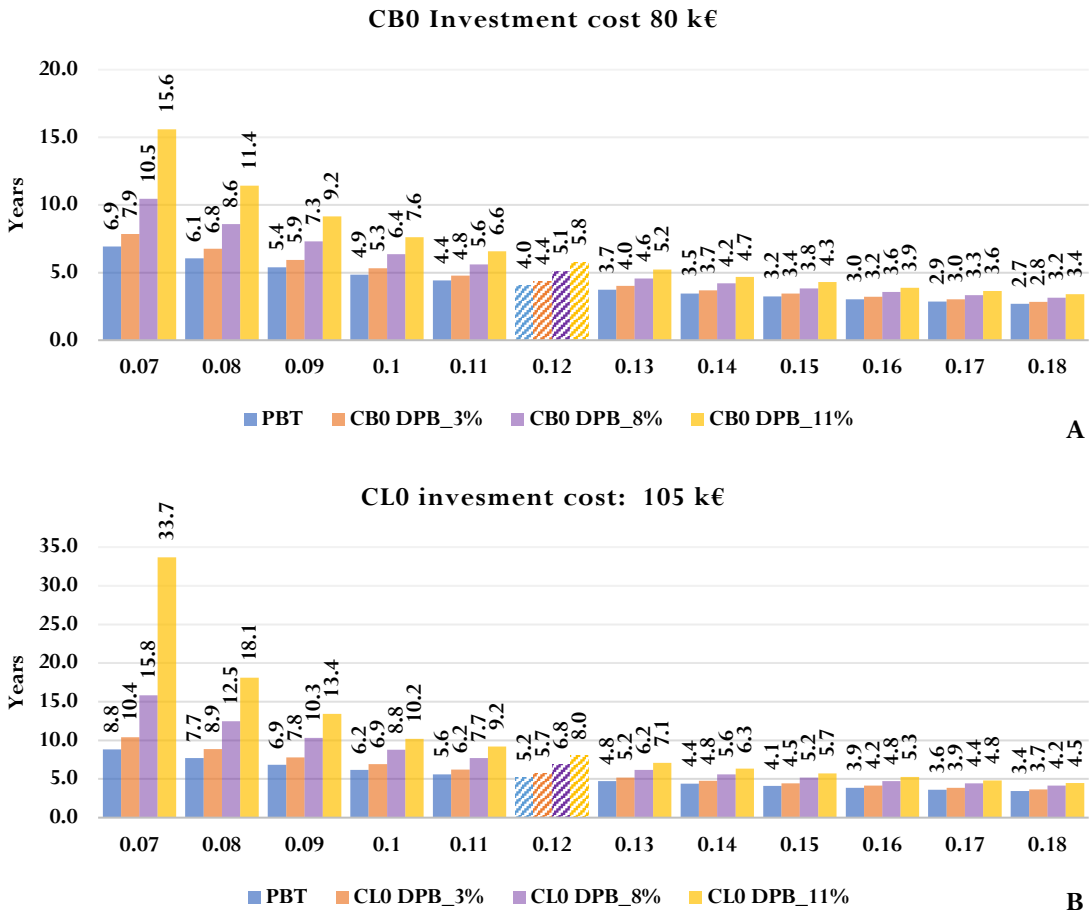

Figure 45: The PBT and DPB for the 3 D%s (3%, 8% and 11%) for CB0 (A) and CL0 (B)

The results of TDEs, SHGs, TCs $C0_2$ emissions and economic feasibilities will be discussed and analyzed further in the next section. The background raw data can be found in the appendices.

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5 Discussion

The focus of this thesis was to study the effects of certain parameters have on the energy performance and thermal comfort of an old building that have retrofitting constraints for a subjective reason rather than logical. The second goal was to make a simple economical assessment of all the successful parameters that resulted in energy reduction. The last step is the evaluation of the realism and applicability of the proposed scenarios.

The results were consistent with the presented theory and offered a deeper insight into the building itself. The simulations confirmed that the building suffers from a substantial thermal mass, is poorly insulated, riddled with leaks and to make matters more complicated the façade with the most windows faced north which added to energy losses by transmission. Indeed, the building was erected to be sturdy and to last, but not to be "comfortable".

5.1 TDE

The results start off with B0 to reproduce the results of [2], thus creating a ground state reference point of comparison for the rest of the inquiry. The building in its basic form consumed around 195 kWh/m^2•yr. The energy partition/division showed a strong location specificity due to the influence of topography, geography and their consequential climate. The B0 located in Gävle consumed most of the delivered energy in the form of heating services, 77%. When the rest of the parameters were applied an interesting result emerged: the 90^0 orientation configuration i.e., B1 scored a slight decrease in heating energy, while B4 led to the highest purchased energy in the study (200 kWh/m^2•yr). The expected result was that turning the façade with the more windows away from the southern side would result in a decrease in the SHGs. The contrary happened as seen in Fig.30. It seemed that the northern façade (with the most WWR) could suddenly receive more solar radiation after the new orientation which might explain the slight increase in SHGs. B1 actually scored highest on the SHGs chart during both the heating and cooling season.

The final parameter, location, used the B0 model as it is at the three remaining global positions. The results were as expected. The enclosed spaces in cold climates need a substantial amount of energy to maintain an acceptable level of thermal comfort, a fact that is abundant in the forementioned literature study. This "need" makes a "blue shift" towards cooling needs as B0 moves towards warmer climates. The model uses electric cooling as a means to counter the cooling load, which was not that effective to create a comfortable dwelling during outside air temperatures greater than 27^{0}C.

The model was then subjected to the same simulation as the B-cases but with the application of LEF, there was a 4.6% reduction in the total delivered Energy. Which is similar to that of [2] if all of the consumed energy was included in the previous study. The LEF has a "constant" reduction of SHGs of 32% that why the variations of L-cases followed the same behavior as the B-cases, but at a lower energy level (parallel behavior).

The two scenarios behaved similarly with L-cases resulting in a reduction in total delivered energy use. The same result achieved by [2]. The comparison between the two cases with respect to

location showed a peculiar result. Warmer locations i.e., Beirut and Jakarta practically had no difference in their energy consumption after the application of LEF. The very slight deviation is a 0.1 kWh/m^2•yr in Beirut and Jakarta in the heating and cooling seasons respectively which was definitely due the reduction in incident solar radiation. The probable heat gain in such countries are energy gains by transmission through the building envelope, keeping in mind that this building has a high thermal mass which influences the cooling load heavily. The other fact that the main model did not include an ideal cooling unit corresponding to the included heater. So, the results EnU of Beirut and Jakarta are heavily underestimated and would need a closer study.

5.2 SHGs

Heat gains from the sun played a vital role when deciding the best configuration that suited each location. It also proved to be a sensitive parameter to consider when applying shadings (internal and external) in cold regions. Any heat gain during the heating season in the colder climates (Gävle and Sapporo) meant less purchased district heat which intern meant less emissions. It was crucial to carefully examine the measures that helped in reducing energy consumption while achieving a comfortable dwelling without compromising on the environmental aspect.

The results in Fig.30 have revealed, as expected, a difference in SHGs when the diverse parameters were applied. The partitions in SHGs told another story that has its foundations in the position of the sun during the heating and cooling seasons as seen in Fig.5 and Fig.15.

The SHGs of B (1-4) during the heating season were relatively stable and comparable to the levels of B0. Even so the effect of blocking out the solar radiation as effectively as in B4 has definitely led to the increase in the delivered energy. This was confirmed by the results of Fig.28 and Fig.30 that were antagonistically compatible i.e., the more SHGs are blocked the more Heat is needed to be purchased. During the cooling season the cooling load due to SHGs varied with the parameters the lowest being B4 with the external awnings.

The impact of location on B0 the results was connected to the influence of the climate. The "blue shift" trend was also evident here, however this time the existence of a heating season was exchanged with cooling season as the climate got warmer (Fig.31).

The other models (L1-4) replicated the same pattern as in the B-case but at a lower scale of SHGs. That was because every parameter was the same except the U-value, g-value and emissivity for the window as seen in Tab.3 for window properties.

In other parts of the world the results showed the same reduction pattern in a range 32-37 % reduction in SHGs. In warmer countries the trapping of long wave heat radiation might increase the cooling load. That would explain why there was an absence of a substantial reduction in the TDE as mentioned before and/or it could also be that the heat enters the envelope (through the walls) by transmission keeping in mind the large thermal mass of the structure. Yet the blocking of incoming solar radiation has managed to minimize SHGs and reduce the need for cooling and as a result the total energy consumption.

5.3 Thermal Comfort

The structure in its basic configuration matched the ones published in [2]. The application of the parameters in B (1-4) have augmented the TC with no exception. The least was B3, while the best result was B4 which according to ASHREA 55 and ISO 7730 was an indication of a thermally comfortable dwelling (see Fig.9). The next index was based on the recommendation of the software IDA-ICE which suggested than B4 was the best configuration where comfort meets metered energy i.e., CME.

The L-cases were on average comfortable confirming the results of [2] and revealing the best stable configuration L4. The resulting PPDs ranged from 9-14% with 9% being according to the standard, satisfies the conditions of a thermally comfortable building. The combination of external shadings with LEF seemed to be working when taking only TC into consideration and according to this study. This was further confirmed by the CME index where all the models, even the L1, scored higher than the B-case indices.

The same simulation was executed at the other geographical locations the best results were chosen and were compared in Fig.41; it was found the Gävle (L4) was most comfortable dwelling followed by Sapporo (L3), Beirut (L4) and Jakarta (L3-4). The cooling season in Gävle did not cause the same inconvenience to occupants (PPD) as the other locations did (see Tab.2 Appendix C).

5.4 Carbon Dioxide emissions

The difference in CO_2 emissions can be found in Fig.42 where B4 sticks out as the global scenario with the highest emissions due to the elevated EnU which was a result of excessive shading of precious SHGs in the heating season. On the other hand, there was the L1 model with an increased SHGS and an educed EnU recording the best emission mitigation scenario. The L0 and L3 had the same emission mitigation making L3 scenario redundant.

5.5 Alternative Energy Supply: GHP

The above scenarios only confirmed the results in [2] when it comes to Gävle. The energy source that feeds the heating needs comes from a DH that is, according to the model, fuel based. Regardless of the source of the fuel there will always be CO_2 emissions. The GHP module replaces the heating need that originates from DH. The results were clear that for the same level of TC as L0 the C-cases resulted in a substantial reduction in EnU, CO_2 emissions and exceedingly better CME.

5.6 Evaluation of parameters

The parameters will be evaluated with respect to the extent of fulfilling the main goal of achieving a reduces EnU, increased TC (in comparison with B0) and reduced emissions.

5.6.1 Performance

5.6.1.1 Orientation

According to the theory, it is a principal factor during the designing phase to orient the façade where the rooms with the highest level of occupancy and WWR towards the southern/northern side depending on which hemisphere the building is located. This was not the case in this model. The northern façade had the highest WWR which could have an effect on the TDE.

The 90^{o} orientation parameter was the least comfortable for occupants, had the highest SHGs, but the lowest energy consumption in both configuration B1 and L1. It was not a realistic scenario for this building, but it showed that the original orientation of the building was not optimal in the terms of modern building design, as discussed above.

5.6.1.2 Internal Shading:

IS has led to a slightly more elevated energy use and as a result an increase in CO_2 emissions in both B and L-cases; that was due to their ability to limit SHGs, second to ES, and providing a relatively thermally comfortable environment for occupants even better than L0. IS was not the parameter of choice because it did not fulfill the goal of reducing energy consumption.

5.6.1.3 External Shading

These were the parameter that had the lowest SHGs which led to an elevated TDE due to an increase in the need for space heating during the cold season; it provided a very thermally comfortable environment for occupants. ES, Like IS, led to an increase in CO_2 emissions and breached the esthetic prohibition of the building. ES has a 32% reduction in SHGs relatively similar to LEF with the difference that ES blocks most of the solar radiation while LEF lets a portion to become part of the internal heat gains.

5.6.1.4 Location

The aim was to see how an old Swedish building that was built for a cold climate would perform in other regions that had a warmer climate (could also be considered as an extreme case of climate change and a global warming anarchy). The scenario of a building like that in those locations would be unlikely yet not impossible, however the study did not include the addition of a cooling unit e.g., Ideal Cooling, to counter the excess heat gains in those climates. Moreover, the effects of heat gains through transmission compounded with the buildings thermal mass made it into a thermally uncomfortable building to live/work in. The result to be expected in such a scenario would be that warmer climates should have a comparable energy need for cooling. The electric cooling in that building was not sufficient enough to create a habitable space, so it could be concluded that those energy consumption figures for Beirut and Jakarta should been higher and in par (at least) with Gävle and Sapporo in both the B- and L-cases.

5.6.1.5 Alternative Energy Supply

The application of GHP gave the best results; combining the research findings in [2] and [6] have led to the choice of changing the source of energy supply in order to bring down the CO_2 emissions provided that the electricity bought for the compressor/pump is from renewable sources. A GHP with a COP of 4.0 generated more energy savings than L0 about 57.5% reduction for CB0 and 59.2 % for CL0.

CB0 resulted in 13% PPD slightly higher than L0; the latter matched CL0 with 11% PPD. There was not much of a difference in the TC values (B0 14%). The main weighting factor of GHP was the energy saving that would put the building on tracks towards the international goals of increasing the BEP. This would be the best retrofit parameter along with insulation of the envelope.

5.7 Economic Feasibility

5.7.1 LEF

The PBT and DPB of L0 was revisited with the motivation that energy prices were rising steadily during the year 2022. The forecasted prices are way beyond what Moghaddam presented and therefore the prices chosen to do the feasibility study did not exceed 0.12 €/kWh. The results were still beyond the 15 years warranty that [2] mentioned: PBT of 16 years and DPB of 22 years. If the prices rise to what was forecasted at the end of 2022 [48] [56] (heating season prices) then both the payback periods should decrease. The D% chosen here was 3%, however if the D% increases then so would the DPB making it infeasible to invest in LEF because of what Moghaddam has already found in the parent study.

5.7.2 GHP

The energy savings of the C-cases amounted to around 20 k€ per year at an energy price of 0.12 €/kWh with a PBT and DPB that were a lot less than that of the LEF case at D% 3 and 5 %. Actually, the energy savings each year with GHP in both cases amounted to nearly 80% of the investment and installation costs of LEF alone. This result in combination with reduced energy use and emissions makes the GHPs a very lucrative retrofitting measure that fulfills the visions of an increased BEP and TC.

5.8 Overall assessment

The study had several factors that were not included in the simulation such as daylight effect on occupants, occupant behavior when the indoor environment was outside their comfort zone, an effective cooling system when the building was studied in warmer locations and a dynamic wind profile other than the urban mode chosen from IDA-ICE database.

The parametric study has confirmed the results of the previous study and revealed new outcomes. The building was indeed in need of a substantial retrofitting measures; the structure suffered of energy leakages/infiltration, high thermal mass, inadequate orientation and an archaic fenestration system. The application of LEF was, in this paper, considered to be a marginal retrofit that could be done to finetune an already energy optimized/retrofitted dwelling. That was not the case with Rådhuset in Gävle which needed a drastic change in its EnU in light of the findings of the parametric study. The retrofit has at least two options that might bring the structure's EnU to an acceptable level and reduce CO_2 emissions:

- Decrease the amount of energy used by reducing leakages and infiltrations (insulation, increase tightness, mitigation of thermal bridges leakage)
- Change the type of energy supply for heating and domestic warm water from fuel to preferably electric powered from renewable sources.

The path that this study has taken after the results of the first B-case simulations was to understand the problem and discover a way that was in par with or better than LEF application, to decrease the EnU of the building without compromising the comfort of its occupants. The initial investment and maintenance costs for the GHP were relatively high, but the DPB was shorter than that of LEF (D% 3-8% and even 11% energy price was greater than 0.08 €/kWh) and fulfilled the goal of finding a better and effective retrofit measure.

The owners or the custodians of Rådhuset should have no problem in accepting an investment that could enhance the energy performance of the building and the public relations with the community of Gävle.

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6 Conclusions

6.1 Study results

Lessons learned from this simulation were that one building code does not fit all meaning that different locations require unique building specifications to ensure the comfort of occupants and also to reduce energy usage. When planning for a retrofit of old buildings, or any structure, it is important to investigate the portion of energy wasted in relation to energy consumed i.e., bought, so that correct measures and investments are prioritized instead of marginal ones. The building sector is facing drastic and dire times with energy prices on the rise.

6.2 Outlook

The municipality should lead the community by example and walk the walk. The building could be compared to a perforated hot balloon: not a very efficient combination. The model should include the missing parameters that were mentioned in the discussion section so that a more holistic result is formed. Photovoltaic cells could be mounted on the roof of the building generating electricity for the compressor and pump of the GHP. The application of LEF should a finetuning the results of a major energy retrofit like insolation and/or alternative energy supply sources.

6.3 Perspectives

The majority of Europe's building stock is pre-1970 with 25% of them were built between 1900s-1700s, moreover there exist multitudes of historical buildings that are in need of a ground-up retrofit so that it induces an impact on the 40% energy use in the building sector and it was forecasted to become 70% by 2050. The global consensus is to reach net zero emissions by 2050 which means that the way buildings are heated (classical boilers, whether operated with gas, biofuel or waste) must change to low carbon heating systems such as GHP, it becomes imperative to have the resolve to be decisive, so that old historical buildings undergo important retrofits to continue existing into the future with a reduced energy, emission footprint and enhance the national or and/or regional energy security while reducing energy price volatility and unpredictability.

Finally, this is from an energy perspective: it is not only what source is being consumed, but how much that is being consumed. Use less before its useless.

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Appendix A

TDE

B-cases

Table 1: Raw data of the B-cases

B-cases		Gävle		Sapporo		Beirut		Jakarta	
B0	Meter	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2
	Lighting, facility	33810.0	22.9	33815.0	22.9	33816.0	22.9	33815.0	22.9
	Electric cooling	1302.7	0.9	5543.6	3.8	21000.0	14.2	53928.0	36.5
	HVAC aux	7102.7	4.8	7610.9	5.2	8192.7	5.6	8479.1	5.7
	Fuel heating	215509.0	146.0	165348.0	112.0	36460.0	24.7	28728.0	19.5
	Domestic hot water	6324.0	4.3	6324.0	4.3	6324.0	4.3	6324.0	4.3
	Equipment, tenant	23087.0	15.6	23091.0	15.7	23091.0	15.7	23090.0	15.7
	Total	287135.4	194.5	241732.5	163.8	128883.7	87.3	154364.1	104.6
B1	Meter	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2
	Lighting, facility	33809.0	22.9	33816.0	22.9	33816.0	22.9	33815.0	22.9
	Electric cooling	1305.3	0.9	5559.5	3.8	21005.9	14.2	54108.0	36.7
	HVAC aux	7146.4	4.8	7652.8	5.2	8193.2	5.6	8479.5	5.7
	Fuel heating	214414.0	145.3	164984.0	111.8	36195.0	24.5	28728.0	19.5
	Domestic hot water	6324.0	4.3	6324.0	4.3	6324.0	4.3	6324.0	4.3
	Equipment, tenant	23086.0	15.6	23091.0	15.7	23092.0	15.7	23090.0	15.7
	Total	286084.7	193.9	241427.3	163.6	128626.1	87.2	154544.5	104.7
B2	Meter	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2
	Lighting, facility	33808.0	22.9	33816.0	22.9	33816.0	22.9	33818.0	22.9
	Electric cooling	1297.3	0.9	5530.4	3.7	20989.4	14.2	53752.0	36.4
	HVAC aux	7060.4	4.8	7544.2	5.1	8187.8	5.5	8478.7	5.7
	Fuel heating	219535.0	148.8	169609.0	114.9	37043.0	25.1	28728.0	19.5
	Domestic hot water	6324.0	4.3	6324.0	4.3	6324.0	4.3	6324.0	4.3
	Equipment, tenant	23088.0	15.6	23092.0	15.7	23091.0	15.7	23092.0	15.7
	Total	291112.7	197.3	245915.6	166.6	129451.2	87.7	154192.7	104.5
B3	Meter	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2
	Lighting, facility	33809.0	22.9	33815.0	22.9	33816.0	22.9	33821.0	22.9
	Electric cooling	1299.4	0.9	5526.7	3.7	20977.5	14.2	53513.0	36.3
	HVAC aux	7097.6	4.8	7599.8	5.2	8190.6	5.6	8478.0	5.7
	Fuel heating	215526.0	146.0	165363.0	112.1	36484.0	24.7	28728.0	19.5
	Domestic hot water	6324.0	4.3	6324.0	4.3	6324.0	4.3	6324.0	4.3
	Equipment, tenant	23086.0	15.6	23091.0	15.7	23092.0	15.7	23095.0	15.7
	Total	287142.0	194.5	241719.5	163.8	128884.1	87.3	153959.0	104.3
B4	Meter	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2
	Lighting, facility	33810.0	22.9	33816.0	22.9	33817.0	22.9	33821.0	22.9
	Electric cooling	1290.1	0.9	5507.2	3.7	20961.4	14.2	53513.0	36.3
	HVAC aux	7030.1	4.8	7467.3	5.1	8168.0	5.5	8478.0	5.7
	Fuel heating	223090.0	151.2	174325.0	118.1	37839.0	25.6	28728.0	19.5
	Domestic hot water	6324.0	4.3	6324.0	4.3	6324.0	4.3	6324.0	4.3
	Equipment, tenant	23089.0	15.7	23092.0	15.7	23091.0	15.7	23095.0	15.7
	Total	294633.2	199.7	250531.5	169.7	130200.4	88.2	153959.0	104.3

L-cases

Table 2: Raw Data of the L-cases

L-cases		Gävle		Sapporo		Beirut		Jakarta	
L0	Meter	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2
	Lighting, facility	33810.0	22.9	33817.0	22.9	33815.0	22.9	33816.0	22.9
	Electric cooling	1296.0	0.9	5520.3	3.7	20981.0	14.2	53639.0	36.4
	HVAC aux	7067.0	4.8	7554.8	5.1	8190.1	5.6	8478.2	5.7
	Fuel heating	202388.0	137.1	157373.0	106.6	36663.0	24.8	28728.0	19.5
	Domestic hot water	6324.0	4.3	6324.0	4.3	6324.0	4.3	6324.0	4.3
	Equipment, tenant	23088.0	15.6	23092.0	15.7	23091.0	15.7	23092.0	15.7
	Total	273973.0	185.6	233681.1	158.3	129064.1	87.5	154077.2	104.4
L1	Meter	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2
	Lighting, facility	33809.0	22.9	33817.0	22.9	33816.0	22.9	33816.0	22.9
	Electric cooling	1299.9	0.9	5536.3	3.8	20991.9	14.2	53877.0	36.5
	HVAC aux	7104.0	4.8	7620.1	5.2	8192.1	5.6	8478.8	5.7
	Fuel heating	201407.0	136.5	157246.0	106.6	36509.0	24.7	28728.0	19.5
	Domestic hot water	6324.0	4.3	6324.0	4.3	6324.0	4.3	6324.0	4.3
	Equipment, tenant	23089.0	15.7	23092.0	15.7	23092.0	15.7	23090.0	15.7
	Total	273032.9	185.0	233635.4	158.4	128925.0	87.4	154313.8	104.6
L2	Meter	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2
	Lighting, facility	33811.0	22.9	33817.0	22.9	33816.0	22.9	33818.0	22.9
	Electric cooling	1291.4	0.9	5506.6	3.7	20962.5	14.2	53454.0	36.2
	HVAC aux	7040.1	4.8	7504.4	5.1	8178.6	5.5	8477.6	5.7
	Fuel heating	205321.0	139.1	160443.0	108.7	37093.0	25.1	28728.0	19.5
	Domestic hot water	6324.0	4.3	6324.0	4.3	6324.0	4.3	6324.0	4.3
	Equipment, tenant	23087.0	15.6	23092.0	15.7	23092.0	15.7	23092.0	15.7
	Total	276874.5	187.6	236687.0	160.4	129466.1	87.7	153893.6	104.3
L3	Meter	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2
	Lighting, facility	33809.0	22.9	33817.0	22.9	33816.0	22.9	33820.0	22.9
	Electric cooling	1293.7	0.9	5506.3	3.7	20943.4	14.2	53247.0	36.1
	HVAC aux	7062.4	4.8	7546.4	5.1	8185.8	5.5	8477.0	5.7
	Fuel heating	202257.0	137.1	157212.0	106.5	36652.0	24.8	28728.0	19.5
	Domestic hot water	6324.0	4.3	6324.0	4.3	6324.0	4.3	6324.0	4.3
	Equipment, tenant	23087.0	15.6	23091.0	15.7	23092.0	15.7	23095.0	15.7
	Total	273833.1	185.6	233496.7	158.2	129013.2	87.4	153691.0	104.1
L4	Meter	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2	kWh	kWh/m2
	Lighting, facility	33811.0	22.9	33817.0	22.9	33817.0	22.9	33820.0	22.9
	Electric cooling	1286.3	0.9	5488.8	3.7	20929.2	14.2	53247.0	36.1
	HVAC aux	7016.6	4.8	7445.3	5.0	8158.5	5.5	8477.0	5.7
	Fuel heating	207794.0	140.8	163639.0	110.9	37625.0	25.5	28728.0	19.5
	Domestic hot water	6324.0	4.3	6324.0	4.3	6324.0	4.3	6324.0	4.3
	Equipment, tenant	23088.0	15.6	23092.0	15.7	23091.0	15.7	23094.0	15.7
	Total	279319.9	189.3	239806.1	162.5	129944.7	88.1	153690.0	104.1

Appendix B

SHGs

Table 1: Raw data of the total SHGs of all the parameters in kWh/yr.

kWh/yr	Gävle									
	B0	L0	B4	L4	B3	L3	B2	L2	B1	L1
Total SHG	51479.1	34955.8	35298.4	24270	51062.6	35173	42116.6	28608	56134.1	38114.8
Heating season (Cold)	9924.8	7840.9	10761.9	8123.9	9928.9	7809.1	10220.9	7831.1	10930.3	8589.7
Cooling Season (Hot)	37486.2	23626.3	20056.4	12725.8	37066.1	23898.4	27770	17302.4	41092.8	26023.9
			0.314316							
	Sapporo									
	B0	L0	B4	L4	B3	L3	B2	L2	B1	L1
Total SHG	59331.5	40321.7	40658.6	27952.5	57683.8	39699	49355.4	33523.7	64696.4	43956.9
Durng Heating season (Cold)	13761.1	10738.2	13924.1	9996.3	13759	10702.8	13804	10312.6	15263.2	11876.5
During Cooling Season (Hot)	40338.4	25443.2	22231.9	14854.3	38686.8	24894.8	30665.2	19500.3	43680.9	27673.2
			0.314722							
	Beirut									
	B0	L0	B4	L4	B3	L3	B2	L2	B1	L1
Total SHG	68791.1	46754.9	46390.6	31880.7	59138.6	40694.1	57058.9	38763.1	78109.1	53063.3
Durng Heating season (Cold)	1112.8	824.6	1353.7	1053.3	1115.8	818.8	1225.9	942.4	1605.3	1320.6
During Cooling Season (Hot)	66882.1	45156	43554.8	29608.4	57223.7	39101.5	54645.4	36761.4	75082.1	50468
			0.325631							
	Jakarta									
	B0	L0	B4	L4	B3	L3	B2	L2	B1	L1
Total SHG	70923.1	48214.6	48441.5	33192.2	49032.6	33357.2	59431.6	40404.3	82442.4	56019.7
Durng Heating season (Cold)	0	0	0	0	0	0	0	0	0	0
During Cooling Season (Hot)	70923.7	48214.4	48441.7	33192.2	49032	33356.8	59430.3	40404.9	82443.6	56019.1

Thermal Bridges

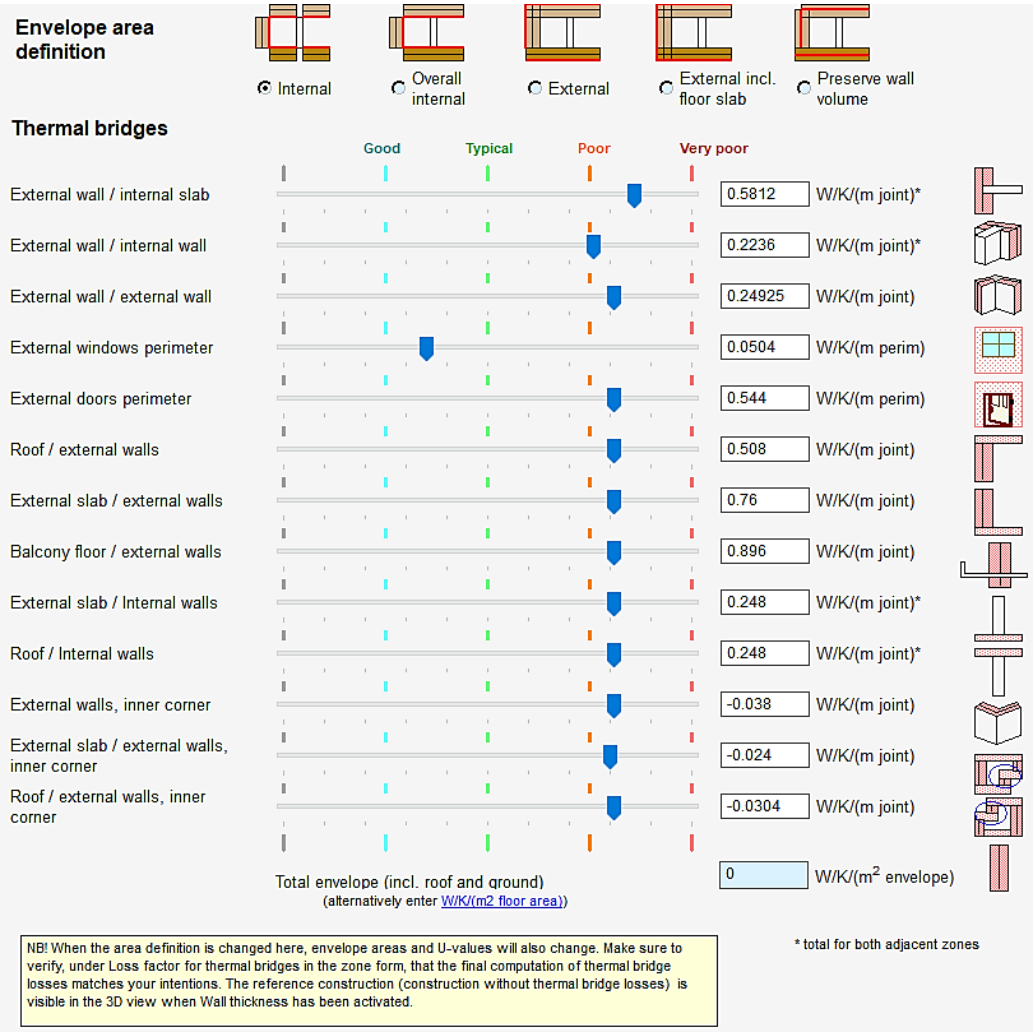

Figure 1: The Poor insulation of thermal bridges throughout the building

Appendix C

Energy Prices July 2022

Table 1: comparison between delivered electricity prices in July 2022 and 2021. a quadruple increase in prices.

Time period	01 July 2022	01 July 2021	Time period	01 July 2022	01 July 2021
00:00	27.1	8.1	12:00	34.9	9.5
01:00	27.8	7.5	13:00	32.3	9.1
02:00	28.1	7.3	14:00	28.6	8.7
03:00	27.9	7.1	15:00	27.3	8.6
04:00	27.8	7.0	16:00	23.7	8.7
05:00	29.6	7.3	17:00	27.2	9.7
06:00	38.1	8.6	18:00	30.3	10.1
07:00	40.7	9.7	19:00	34.5	10.5
08:00	41.3	10.0	20:00	37.7	10.1
09:00	40.6	9.7	21:00	32.7	10.1
10:00	38.6	9.6	22:00	40.3	9.9
11:00	38.1	9.8	23:00	38.0	8.9

Table 2: Best TC data with respect to location

Location	Gävle	Sapporo	Beirut	Jakarta
Parameter	L4	L3	L4	L3-4
% h opT>> W27	19	44	89	100
% h opT>> Av_27	8	29	65	100
PPD	9	18	45	92
Total Delivered Energy	189.3	158.2	88	104.1
Comfort per Energy	0.481	0.518	0.625	0.077