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The effects of low-emissivity window films on thermal comfort and energy performance of a historic stone building in cold climate: computer simulations with “IDA ICE”

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Preface

I would like to thank my parents for their unlimited support, specially my mother who has always encouraged me to continue studying towards higher education. I would also like to thank my supportive supervisors Mr. Arman Ameen and Mr. Magnus Mattsson who have really helped me to accomplish this project. Finally, I would like to thank all the members of University of Gävle who have given me the opportunity to study here.

Abstract

Low-emissivity (low-E) window films are designed to improve the energy performance of windows and prevent indoor overheating by solar radiation. These films can be applied to different types of glazing units without the need for changing the whole window. This characteristic offers the possibility to improve the energy performance of the window of old and historic buildings for which preservation regulations say windows should remain more or less unchanged. This research aims to figure out to what extent a low-E window film can improve thermal comfort and energy performance of an old three-storey historic stone building in the cold climate of Mid-Sweden. In this research, first, with help of the simulation software “IDA ICE”, the entire building was modelled without window films in a one-year simulation. Second step was to add the low-E window films (3M Thinsulate Climate Control 75 (CC75)) to all the windows and repeat the simulation. Comparison between the results of the two cases revealed an improvement in energy use reduction as well as the thermal comfort when applying the films. For the application of the window films, a cost analysis using payback method was carried out which showed a long- time payback period. Although an investment with a long-time payback period is considered as a disadvantage, for historic buildings with very strict retrofit regulations specially when it comes to the building’s facades, application of the low-emissivity window films for better energy performance and thermal comfort is among the recommendable measures, but not necessarily the best.

Keywords: Low-E window films, low-emissivity film, thermal comfort, low-E materials, solar heat gain, IDA ICE, building energy saving measures, heating demand, cooling demand.

NOMENCLATURE

The symbols that were used in this study are presented here.

Symbol	Description	Unit
T	Temperature	K
U- value	Value of the thermal transmittance	W/m^2K
G-value	Fraction of solar radiation entering the building	–
VT	Visible transmittance	–
Low-E	Low-emissivity	–

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1 Introduction

1.1 Background

Nowadays one of the big issues of the world is global warming caused by fossil fuels which are known as the largest energy supply of the globe, hence there is an urgent need for a switch from fossil fuels to renewable sources of energy. Besides this transformation, different energy saving measures should be developed, because the world energy demand can be reduced to a great extent by these measures. “A significant portion of the total primary energy is consumed by today's buildings in developed countries” (Suresh B.Sadineni, 2011)”. “Energy usage in buildings represents about 40% of the total energy usage in Europe” (Bjørn Petter Jelle, 2015). It is reasonable to say that there is a big potential for reducing the energy use of the buildings sector which can lead to less consumption of fossil fuels thereby protecting the environment.

1.2 Literature review

This chapter reviews the collected peer-reviewed journal articles and some other sources.

Transparent areas such as windows and skylight glazing in buildings have always attracted designers' attention since they provide building with natural light, ventilation and beauty. Nowadays, there is a trend in increasing the window areas in buildings due to the fact that modern architecture has embraced transparent areas enlargement as well as the use of glass as curtain wall. Along with the above-mentioned reasons, there is another important reason that has increased the importance of windows in building, and that is the significant role which they play in the energy use of buildings. As it is mentioned before, the amount of energy needed for lighting, cooling and ventilation can be reduced using windows, but at the same time there are some important disadvantages associated with windows that should be taken into consideration.

Larger window areas provide the building with more natural light and natural ventilation resulting in some reduction in the buildings energy usage. It should also be taken into account that sometimes the benefits from sunlight can be penalized by the excessive solar gain through windows (Rongxin Yin, 2012).

Bjørn Petter Jelle (2015) says a large portion of energy in buildings is used to meet the heating and cooling demand. The transparent areas of buildings including windows and skylight glazing are responsible for a substantial part of the energy loss resulting in an increase in buildings' energy usage.

It can be said that in the summer, high level of heat radiation transferred into the buildings through windows can cause overheating which can lead to an increase in cooling demand. On the other hand, in the winter the radiative heat transferred to the outside of buildings through windows, can increase the heating demand. In both situations the energy consumption of buildings rises which will result in the energy cost growth of buildings and environmental implications.

The reason why windows with typical clear glasses are considered as important sources of heat loss in the winter and heat gain in the summer is that they usually have high U values and SHGC (solar heat gain coefficient). Jong Jun Park (2017) mentions that Although windows provide buildings with light, views and fresh air, they are responsible for about 20 % - 40 % of energy losses in buildings due to their high U-value compared to the other parts of buildings.

A building's energy usage can be affected by façade-related properties of a glazing system including U-value, G-value, shading, daylight factor and light control (J.W. Lee, 2013).

To reduce the heat loss and excessive heat gain through windows, a wide range of methods and techniques have been developed by researchers and companies and it is likely to see even more advanced technologies and methods in near future.

Reducing heat loss through windows is not as easy as reducing heat loss through walls. In order to reduce heat loss through windows, a wide range of methods can be adopted such as the air layer thickness of double-pane windows optimization, evacuating the cavity, coating pane surface with low-emissivity materials, increasing the number of the windows' panes, filling the cavity between panes with an inert gas or adopting some these methods simultaneously (Müslüm Arıcı, 2014).

In addition to the above-mentioned methods, installation of blinds can also improve energy performance of buildings.

Application of blinds can contribute to the building's energy usage reduction in two different ways. Firstly, the blinds reduce the window's G-value resulting in less solar gain, thereby decreasing the cooling demand. Secondly, the blinds decrease the heat loss through the window resulting in some reduction in U-value of the window, although the effect depends on the slat angle (Karjalainen, 2019).

Sudip Kumar Pal (2015) also mentions some attractive advanced glazing systems including electrochromic (EC) glazing, photovoltaic (PV) integrated glazing, self-cleaning glazing, and vacuum glazing. Many of the above-mentioned methods seem complex and costly, since majority of them cannot be applied to the existing windows or old windows and they require window replacements.

The following paragraphs will focus more on one of the simplest methods of window energy performance improvement which is the application of low-E (low emissivity) materials to the windows. Low-E window films can contribute to the reduction of solar heat gain by reflecting the near-infrared radiation of the sun, thereby reducing the cooling demand in the summer. They can also help to keep the indoor climate warm by blocking and sending back the heat radiation from objects and other sources of heat in the buildings, thereby decreasing the heating demand in the winter.

Figure 1 indicates the Solar energy distribution with respect to wavelength which is drawn from (Bjørn Petter Jelle, 2015).

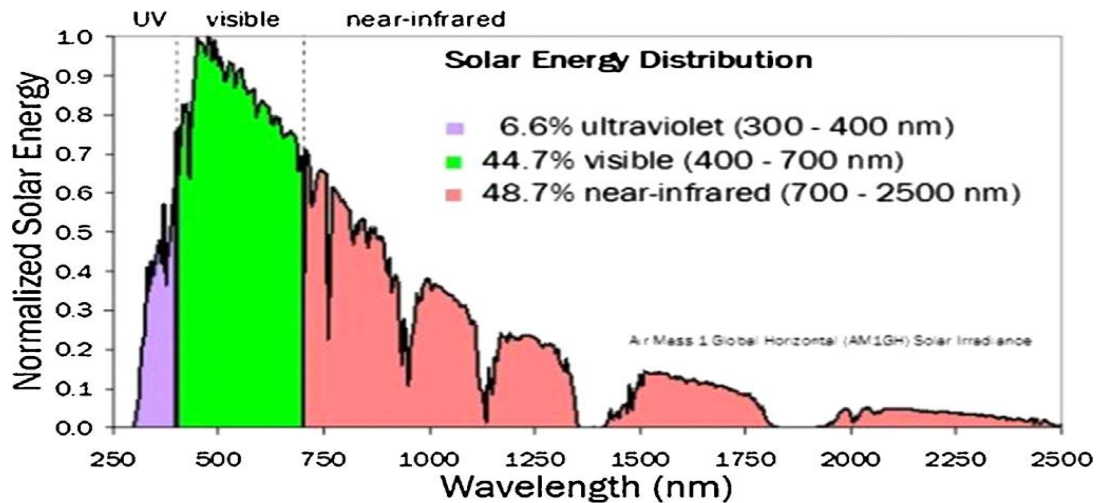


Figure 1. Solar energy distribution with respect to wavelength

Bjørn Petter Jelle (2015) has discussed different methods of applying low-e coating to glazing units including hard coatings, soft coatings, self-applicable films and suspended films.

The first two of the above-mentioned methods should be adopted and implemented by manufacturers before the installation, but the third method which is self-applicable film can even be implemented after the installation of the windows. It means that this method does not require windows replacement, thereby giving the opportunity to equip windows of old buildings with low-E films that can improve the energy performance of the buildings.

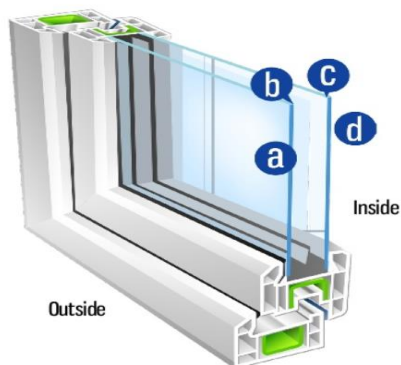


Figure 2. An ordinary two-pane window

Figure 2 shows an ordinary double-pane window drawn from (Windows, 2015). It is suggested that for a cold climate it is better to apply the low-E coating to the outward-facing surface of the inner pane (surface c), so it can reflect the heat back to the room, thereby reducing the heat loss.

There are some factors that can affect the benefits of the use of window films, including the climate in which the building is located which itself decides whether the main focus should be on excessive solar heat prevention or indoor heat loss prevention, seasonal variations, aging of the films and shading caused by outdoor objects, e.g. trees.

Applying a low-E window film without considering the above-mentioned factors may minimize the benefits of low-E films, for instance the value of the energy that is saved by using a low-E window film in the summer, can be less than the value of the heating load that could have been received from the sun in the winter in the absence of low-E films.

There are other important factors that should be taken into account including visible transmittance (VT) and UV radiation. Although the window films protect the building from UV radiation, the amount of sunlight transmitted into the building can be affected by Low-emissivity window films (Penny, 2012).

However low-E films do not transmit visible light as well as a clear glass, they still provide occupants with the desired light.

The same as any other methods, low-E window films can have some drawbacks that should be taken into account, including creation of bubbles on the film in case that film is not installed correctly, reduction in transmission of visible light which results in using more artificial light which rises the electricity demand of the building.

To be able to identify the positive effects of low-E window films on the entire building, one way is to conduct experiments to compare the energy performance of some of the windows in both situations, in the presence and in the absence of window films and then using a building energy simulation software to estimate the impact of the low-E window films on the energy performance of the entire building.

There have been several studies regarding the effects of low-E window films on the energy performance of buildings located in different climates, for instance Rongxin Yin (2012), explains a research regarding the effects of a solar control film (applied to a double-glazing unit) on reducing the annual energy consumption and peak demand load in the summer. It is mentioned that the heat gain through windows can drop by 55% by applying window films to the outward-facing surface of the inner pane comparing to the glazing unit without the films.

The results of a field test carried out to investigate the energy performance of a building's windows equipped with solar films revealed that the solar heat rejection of the window was 30 % for diffused radiation and 50 % for beam radiation. Finally, it was concluded that solar films under the Hong Kong climate can contribute to a AC energy reduction (Chunying Li, 2015).

It can be concluded that windows are among important contributors to the building heat loss in the winter, because windows usually have higher U values than other parts of a building. Although glazing units provide natural light, ventilation and beauty for the building, they can cause overheating in the summer by transmitting solar heat radiation into the building. In order to develop the energy performance of windows, a wide range of methods from using high-tech and complex windows to low-E window coating and window films have been adopted. Among these methods, low-E window films have attracted researchers' attention

because they can be applied to the existing windows without a need to replace them. The effects of some of the low-E window films on the energy performance of the entire building in some locations have been tested by conducting experiments and using simulation software and the results have made researches optimistic about the application of low-E window films.

1.3 Aim

This research has tried to figure out to what extent low-E window films can reduce the heating demand of a building in the winter and to what extent they can prevent overheating in the summer. The main purpose is to estimate the effects of one specific low-E window film named “3M Thinsulate Climate Control 75” on the energy performance and thermal comfort of an old three-storey stone building named “Rådhuset” (the old city hall) located in Gävle. In addition to the energy performance and comfort analysis, a cost analysis has been conducted to evaluate the cost-effectiveness of the window film application to this building.

1.4 Approach

The window films of the above-mentioned type were already applied to some double-pane windows of the studied building and some data regarding the U values and visual light transmittance of the windows in the absence and presence of the window films collected by researchers at University of Gävle. Now the main purpose of this research is to estimate the effects of this type of window film on the energy performance and thermal comfort of the entire building with the help of the simulation software “IDA ICE”.

2 Theory

2.1 Building Energy Balance

Energy is supplied to buildings in different forms to provide them with electricity, space heating, space cooling, hot water etc.

“A building’s energy balance is the relationship between the energy that is supplied to the building and the energy that is lost” (Åberg, 2014).

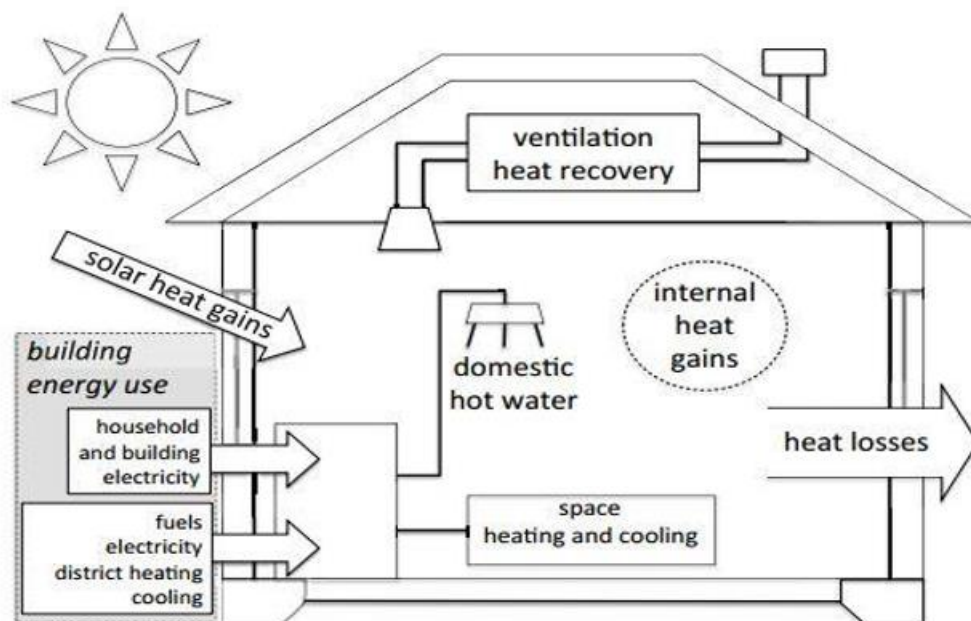


Figure 3. Energy balance of a building component

Figure 3 derived from Åberg (2014) illustrates the energy supply and energy losses constituting the energy balance of the building. Solar heat gains along with internal heat gains generated by the occupants and appliances contribute to heating the building. Heat can be lost as a result of heat transmission, infiltration and ventilation. Heat transmission losses occur through windows, doors, walls and roof.

2.2 Heat Transfer

Heat can transfer through conduction, convection and radiation. The following sections elaborate on each of them.

2.2.1 Conduction

Conduction is the flow of heat through a material by direct molecular contact. This contact occurs within a material or through two materials in contact (Taghi Karimpanah, 2018).

$$\dot{q} = -k \times A \times \frac{dT}{dx} \quad \text{Eq. 1}$$

Where \dot{q} = heat transfer rate (W)

K = thermal conductivity of the material (W/m.K)

A = heat transferring area (m^2)

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

2.2.2 Convection

Convection is the transfer of heat by the movement or flow of molecules (liquid or gas) with a change in their heat content. This is an important heat transfer mode between fluids and solids, or within fluids (Taghi Karimpanah, 2018).

$$\dot{q} = hc \times A \times (T_w - T_\infty) \quad \text{Eq.2}$$

Where \dot{q} = heat-transfer rate (W)

A = heat transferring area (m^2)

hc = convective heat transfer coefficient (W/m² K)

T_w = temperature of the solid surface (K)

T_∞ = temperature of the fluid (K)

2.2.3 Radiation

Radiation is the transfer of heat by electromagnetic waves through a gas or vacuum. Heat transfer by this mode therefore requires a line of sight connection between the surfaces involved (Taghi Karimpanah, 2018).

$$\dot{q}_{emitted} = \sigma \times A \times T^4 \quad \text{Eq.3}$$

Where $\dot{q}_{emitted}$ = blackbody emitted radiation (W)

A = heat transfer area (m^2)

T = absolute temperature of the blackbody (K)

$\sigma = 5.6703 \times 10^{-8} \text{ (W/m}^2\text{k}^4\text{)}$ - The Stefan-Boltzmann Constant

2.3 U-value

The U-value of a material indicates the amount of heat that can be transferred through one square meter of the material when there is a one degree Celsius difference in temperature across the structure ($\text{W/m}^2\text{K}$)” (WIKIPEDIA, 2019).

2.4 G-value

The G-value which is mostly used in Europe, is the coefficient indicating the fraction of solar radiation passing through the window. Despite having minor differences in modeling standards compared to the SHGC, the two values are effectively the same. The maximum amount of G-value is 1 representing full transmittance of all solar radiation while the minimum G-value is 0.0 representing a window with no solar energy transmittance (WIKIPEDIA, 2019).

2.5 Visible transmittance

Visible transmittance is the fraction of visible light transmitted through a window (Windows, 2015).



Figure 4. Solar visible transmittance

2.6 Thermal comfort

“Thermal comfort’ is the term used to describe a satisfactory, stress-free thermal environment in buildings and, therefore, is a socially determined notion defined by norms and expectations” (J. Fergus Nicol, 2017). According to ASHRAE Standard 55-2013, thermal comfort is that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation.

2.7 PMV/PPD Model

PMV/PPD model is one the accepted models for determining thermal comfort.

Predicted Mean Vote (PMV):

The PMV model developed by Fanger (1970), is widely accepted and used in standards (ASHRAE 55, 2013; ISO 7730, 2005) and by practitioners to evaluate thermal comfort. It is an index that predicts the value of the mean votes of a large group of persons on the ASHRAE thermal sensation scale (Kabanshi, 2018)

Figure 5 shows ASHRAE thermal sensation scale.

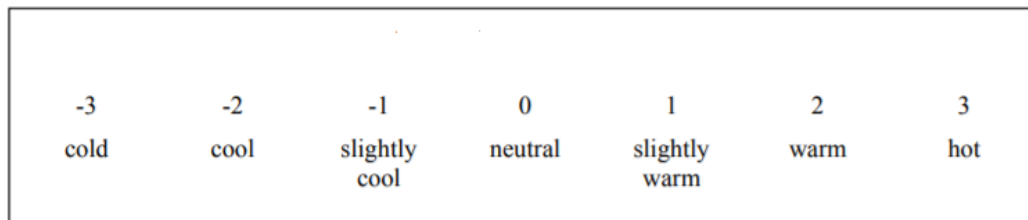


Figure 5. ASHRAE thermal sensation scale

Predicted Percentage Dissatisfied (PPD):

It is an index that predicts the percentage of thermally dissatisfied people (Kabanshi, 2018). The standard ranges for PMV and PPD are as follows:

Comfortable range: $-0.5 < \text{PMV} < +0.5$

Acceptable: $\text{PPD} < 10\%$

2.8 Standard (EN-15251)

In the area of thermal comfort, the international standards commonly used to evaluate the thermal environments are (ISO7730-2005), (ASHRAE55 2013) and (EN-15251-2007).

The EN 15251 standard is used to structure thermal comfort guidelines. This standard uses special quantities including PMV and PPD, which can be computed as a field and visualized in post-processing (Anon., u.d.). The EN-15251 standard gives the opportunity to conduct building energy usage calculations in a way that comfortable and healthy indoor environment is achieved (J. Fergus Nicol, 2011).

More detailed information regarding the EN-15251 standard can be found in Appendix A.

2.9 IDA ICE

Nowadays simulation software is widely used to estimate the energy performance of buildings and HVAC systems. IDA ICE is among the reliable simulation tools which with the help of mathematical models giving the users the opportunity to be aware of the heating and cooling load, thermal comfort and indoor air quality in a building (Arefeh Hesaraki, 2013).

IDA ICE 4 was first developed at KTH Royal Institute of Technology and the Swedish Institute of Applied Mathematics, ITM. Validation of this programme was conducted by some studies.

According to the set indoor temperature, the energy balance of the building is calculated using finite difference method, timesteps simulation and transient calculations (Ahmed, 2017)

The main disadvantages of this programme include the risk of unexpected program crashes and errors in mathematical model creation during simulation (Arefeh Hesaraki, 2013).

2.10 Payback Period Method

The payback period is the period of the time that an investor waits for the initial investment to completely return (Kagan, 2019). It can be said that the shorter payback period, the more willingness to invest. One limitation of this method is that it does not take the interest rate into consideration.

The following formula shows the calculation of the payback period without considering the interest rate (Robert Kasproicz, 2015).

$$\text{payback period} = t = \frac{\text{initial invest cost}}{\text{revenue} - \text{energy cost}} \quad \text{Eq. 4}$$

2.11 Discounted payback period (DPP)

The discounted payback period (DPP), which is the period of time required to reach the break-even point based on a net present value (NPV) of the cash flow, considers the time value of money (Calculator.net, 2019).

$$\text{Discounted Payback Period} = \frac{-\ln\left(1 - \frac{\text{investment amount} \times \text{discount rate}}{\text{cash flow per year}}\right)}{\ln(1 + \text{rate})} \quad \text{Eq.5}$$

3 Method

3.1 Study object

In this research the effects of a specific low emissivity window film on the energy performance of a historic building in Gävle called “Rådhuset” has been analysed. The window film that was selected for this building is named “3M Thinsulate Climate Control (CC75)” manufactured by “3M company”. The entire building was modelled with the help of the simulation software IDA ICE 4.8 licensed by “EQUA Simulation company” located in Sweden. This programme offers the possibility to create a 3D model of the building and divide it into different thermodynamic zones and input all the data regarding the construction and energy performance of the building. By using this software there is a possibility to run simulations for different periods of the year. After creation of the model of the building known as the basic model, it is time to validate the model, then the intended changes to the basic model can be made and its results should be compared with the base model. This software offers an option to compare the results of two models, so a simulation preferably for the whole year should be carried out and its results must be compared with the energy bills of the building. For the results of the simulation to be valid, they are usually expected to be maximum 5% deviant from the energy bills. After the validation of the model, the window films can be added to all the glazing units of the building to run a new simulation. Finally, the software offers an option to compare the results from the new simulation with the basic model in order to evaluate the effects of the window films on the energy performance of the building.

3.2 Procedure

Previously a research group at Gävle university (Magnus Mattsson, 2018) sponsored by Swedish Energy Agency, conducted a field test in Rådhuset to measure the U-value and light transmission of his type of window film attached to the outward-facing surface of the inner pane (surface c) of the window of the building (see Figure2). To measure those values, a hot box was created around the window and then all the measurements were carried out and recorded (see Appendix B). In this research study, the input data regarding the window film is based on the results of the above-mentioned field test. To evaluate how the energy performance of the building could be affected due to applying the window films to all the glazing units of the building, first the building in the absence of the window films was modelled with the help of the simulation software IDA ICE 4.8 and called case A. The input data needed to make the model of the building were collected from a group at Gävle university studying this building. To get a more accurate model, during the model creation process, the input data and other parts of the model were compared with an existing model of this building previously created by another group at Gävle university.

The following paragraphs will discuss the most important building's data imported to the software. The illustrations were captured while the creation of the model was being done.

3.2.1 The building's model creation on IDA ICE

- **Location and climate data**

As mentioned before, the building is located in Gävle, therefore, Gävle climate file was chosen for this building.

- **Building layout**

The following figures depict the floors' plan together with the orientation of the building. Regarding the opening units in the following figures, the yellow rectangular shows the door and the blue one shows the window.

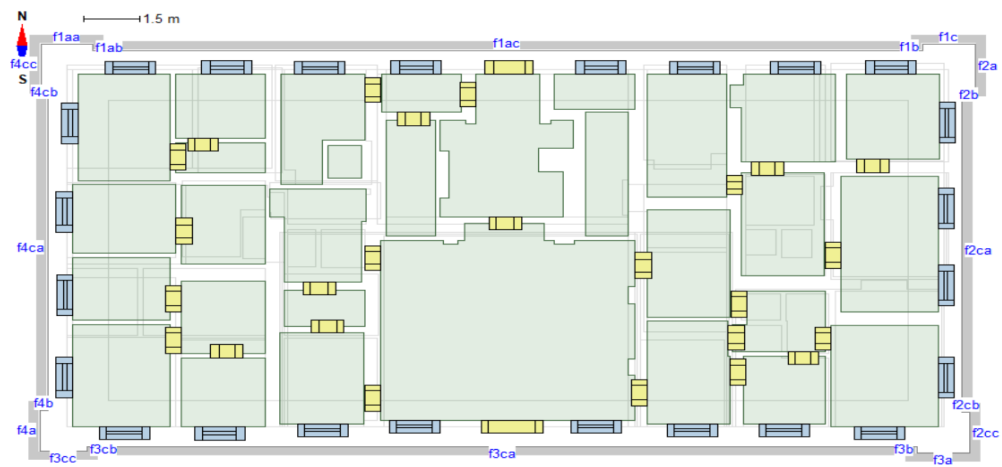


Figure 6. First floor's plan and orientation

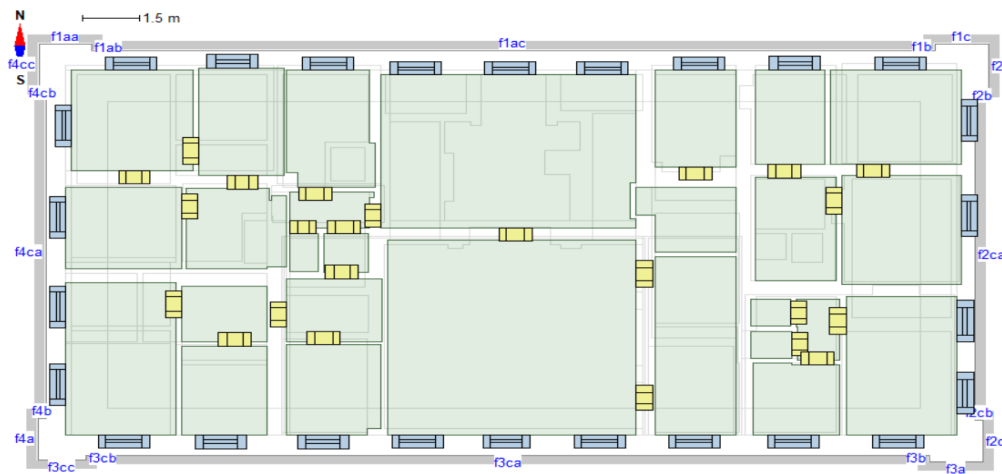


Figure 7. Second floor's plan and orientation

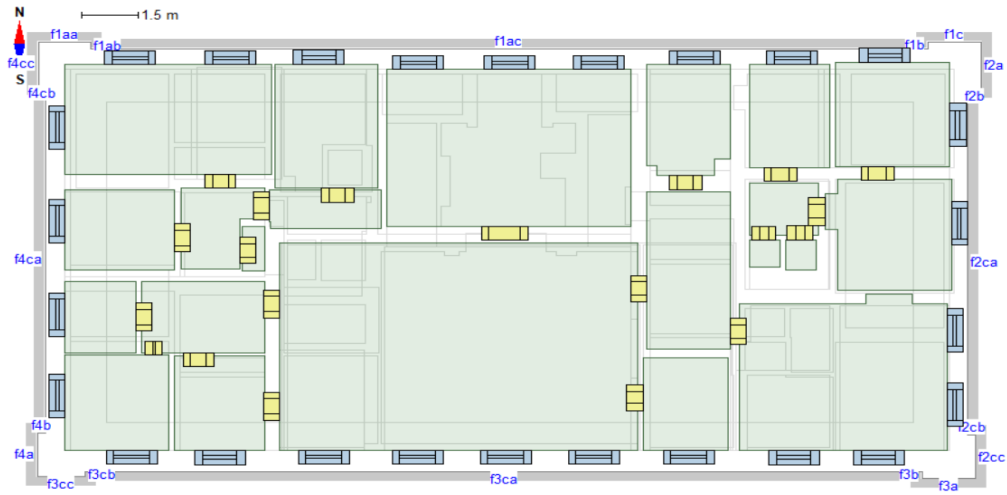


Figure 8. Third floor's plan and orientation

- **Building's construction data**

Table 1 shows the building's construction data previously collected by another group at University of Gävle.

Table 1. Building's construction data

Construction	Material	Thickness (mm)	Thermal conductivity (W/m.K)	U-value (W/m ² .K)
External walls	Render Brick Render	10 600 10	0.8 0.58 0.8	0.81
Internal walls	Render Brick Render	2 400 2	0.8 0.58 0.8	1.16
Internal floors	Wood Sand Chip board Floor coating	45 250 50 20	0.14 0.33 0.037 0.18	0.37
External floors	Floor coating Concrete	5 250	0.18 1.7	2.9
Roof	Wood Sand Chip board Floor coating Brick Light insulation	45 250 50 20 100 50	0.14 0.33 0.037 0.18 0.58 0.036	0.23
Basement wall towards ground	Render Concrete	10 200	0.8 1.7	3.3

- **Thermal bridges**

The first four rows in Figure 9 was measured by a group at University of Gävle, but for the rest, it was tried to estimate the values and no measurements were conducted.

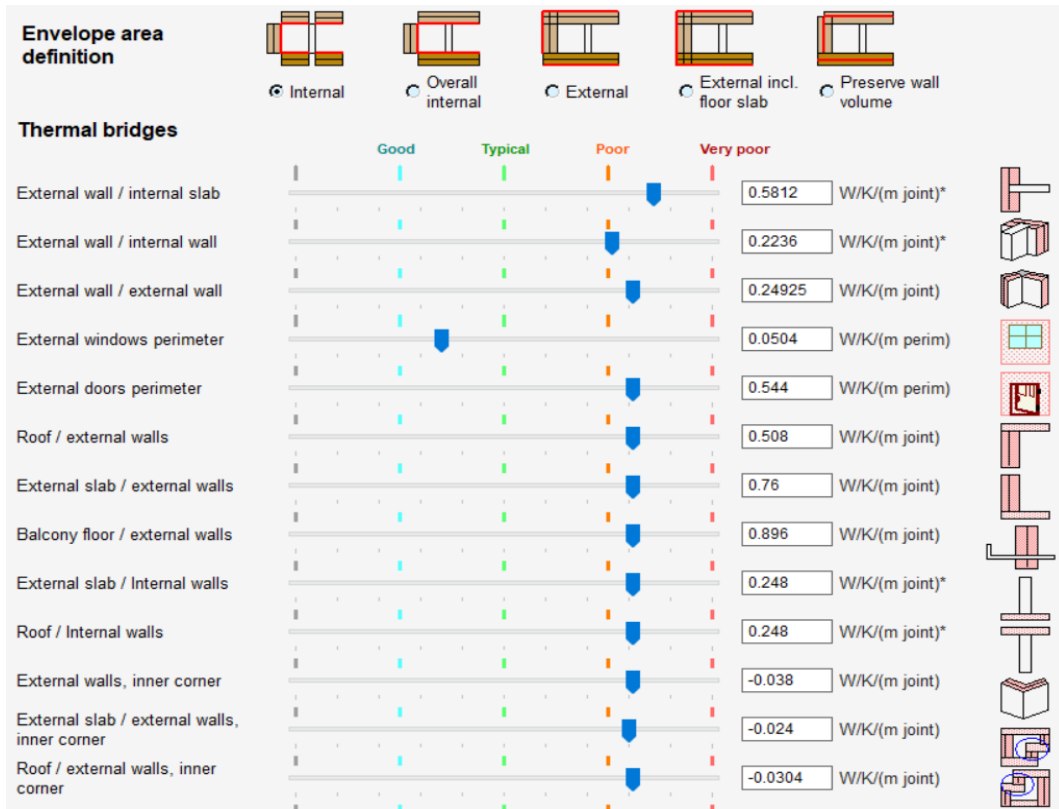


Figure 9. All the thermal bridges

- **Description of the HVAC system**

The HVAC system was modelled by a standard air handling unit. The air handling unit is a constant air volume system (CAV) for which the supply air and return air is 1.3 L/s.m^2 .

- **Internal temperatures and infiltration rate**

According to the data collected from the report of a group at university of Gävle, the indoor temperature was adjusted between 21°C and 23°C . Regarding the infiltration rate, the wind driven flow method on IDA ICE was chosen. The results of the measurements previously carried out with the help of a blower door, shows the air tightness equal to 0.84 L/s.m^2 at the pressure difference of 50 Pa.

- **Internal heat gain and occupancy**

All the detailed information regarding the lighting system, number of occupants in each zone, the equipment and radiators in each zone along with their operation schedule can be found in Appendix C. Totally 59 occupants with 59 units for equipment (each unit with the power of 125W) was considered. The activity level for each person was 1.2 metabolic equivalent (MET), and operation schedule was adjusted between 6:00 and 18:00 on weekdays.

- **Heating and cooling system**

There are certain number of radiators in each zone which are all supplied by district heating and the power of them was adjusted according to each zone characteristics (see Appendix C). The domestic hot water is also supplied by the district heating and there is a heat pump for cooling with the COP of 3.

- **Glazing units input data**

Regarding the glazing units of the building, it is a double-pane clear glazing with a wooden frame. The data regarding the U-value, G-value and visible transmittance of the window for both cases, without the window films and in the presence of the films are shown in the following table. As it is mentioned before, these values are collected from a field test carried out by (Magnus Mattsson, 2018) together with the technical catalogue of the window film provided by the manufacturer (see Appendix D).

Table 2. Glazing units input data for case A (without films) and case B (window films)

	The whole window without low-E films	The window with low-E films on the third surface
U-value ($W/m^2 K$)	2.30	1.59
G-value	0.76	0.51
Visible Transmittance	0.81	0.66

- **3D model of the building**

Figure 10 depicts the 3D model of the building. the building totally has 76 windows.

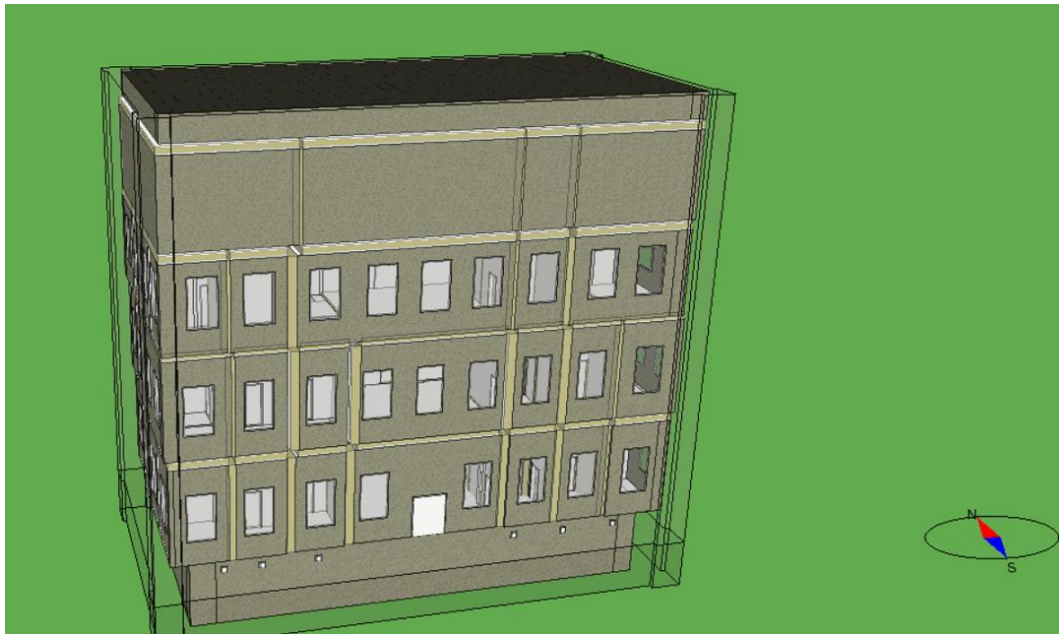


Figure 10. The 3D model of the building

3.2.2 Validation of the model of the building

After inputting all the data and completing the model, a simulation for the period “01.01.2018 to 31.12.2018” was run. The reason why the simulation was run for the entire year 2018 was that the field test by (Magnus Mattsson, 2018) was carried out in 2018. The results of the simulation were extracted and in order to validate the model, the energy use for district heating derived from the simulation was compared with the annual district heating bills of the building collected from Gavlefastigheter company. Since the inside areas of the building are heated by radiators and the air handling units supplied by the district heating network, only the energy usage from district heating was chosen for the validation purpose. Usually less than 5% deviation from the reference value (energy bills) is accepted.

3.2.3 Application of the window films

After the validation of the building’s model (case A (without the film)), by adding the window films to all the glazing units of the building, case B was created. It can be done by inputting U-values, G-values and visible transmittance value in the presence of the window films collected from the previous field test (see Table 2). The next step was to run a simulation for the same period as the basic model (case A (without films)) and collect the results.

3.2.4 Comparison of the results of case A (without films) and case B (with films)

The main areas for the comparison include energy usage of the building along with thermal comfort with the help of Fanger's comfort indices and the EN-15251 standard.

To compare the results of the two cases regarding thermal comfort, for each case, totally four zones from all the three floors covering all the four facades of the building were chosen. In the selection process, the priority was given to the zones which have more occupants and windows. Then the data for the chosen zones for the both cases were compared against each other.

The following figures show the orientation of the chosen zones.

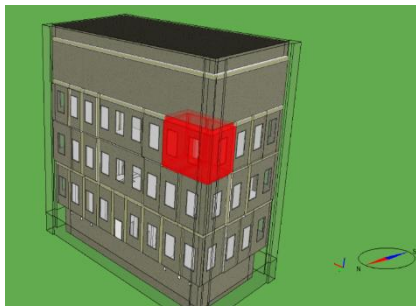


Figure 11. Zone 4 facing the north and west

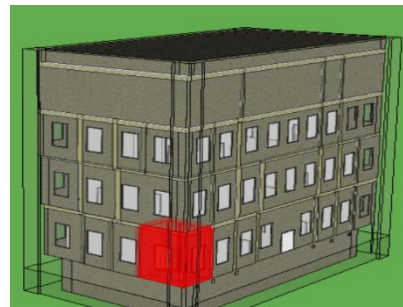


Figure 12. Zone 14 facing the west and south

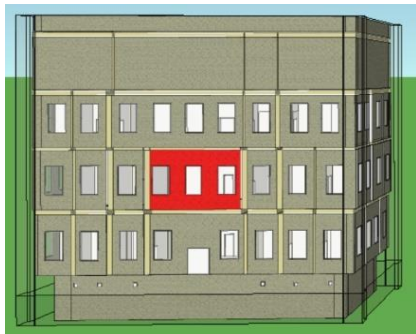


Figure 13. Zone 44 facing the south

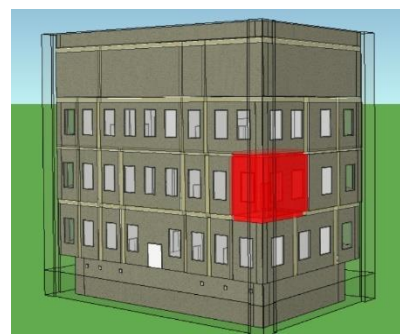


Figure 14. Zone 56 facing the east and south

3.2.5 Cost analysis using payback period and discounted payback period (DPP) method

Finally, the cost analysis using payback period method and discounted payback period (DPP) (see the theory part) was conducted to evaluate the energy cost savings of the application of the low-E window films to the building.

3.3 Problems and limitations of the adopted method

One of the important issues associated with simulation of the building for the entire year, was its long duration, it was time consuming. This disadvantage hinders the project in case that redoing the simulation caused by wrong input data is needed.

It could be good to mention that the uncertainty about the energy price for the next years could be a problem. It is very difficult to predict the energy price because it depends on many factors. In this report the energy price for the whole 15 years chosen for the analysis, was considered constant.

Another weakness of the adopted method was that in the aforementioned field test, the low-E window films were tested only on limited number of the buildings' glazing units and it means that the U-values and g-values of the other glazing units located in other parts of the building in the presence of the films might slightly differ from the collected values from the field test. Other factors including shading due to trees and outdoor objects and aging of the films could also affect the accuracy of the results.

4 Results

In this chapter the results of the simulation without the window film (case A) and with the window films (Case B) will be presented.

4.1 Base model simulation results (case A (without window films))

The simulation results regarding the energy performance and thermal comfort will be discussed separately in the following parts.







4.1.1 Energy Performance

The results of the base model simulation (case A (without films)) are illustrated in the following tables.

Table 3. Building information.

Delivered Energy Report	
Building	
Model floor area	1475.8 m ²
Model volume	5195.6 m ³
Model ground area	213.5 m ²
Model envelope area	1909.6 m ²
Window/Envelope	10.9 %
Average U-value	0.9466 W/(m ² K)
Envelope area per Volume	0.3675 m ² /m ³

Table 4. Simulated energy use of the building.

		Purchased energy		Peak demand
		kWh	kWh/m²	kW
	Lighting, facility	33809	22.9	10.8
	Electric cooling	1314	0.9	9.0
	HVAC aux	7093	4.8	2.33
	Total, Facility electric	42216	28.6	
	Fuel heating	215548	146.1	88.15
	Domestic hot water	6324	4.3	0.72
	Total, Facility fuel*	221872	150.3	
	Total	264088	178.9	
	Equipment, tenant	23087	15.6	7.38
	Total, Tenant electric	23087	15.6	
	Grand total	287175	194.6	

*heating value

Table 4 shows the amount of energy delivered to the building. As illustrated, the total energy usage of the building for heating and domestic hot water is 221872 kWh for the whole year. The amount of electricity use for cooling is also 1314 kWh which is quite smaller than the amount of energy used for heating.

Table 5. Heat losses and heat gain during heating and cooling for the entire building

All zones

kWh (sensible only)


















Month	Envelope & Thermal bridges	Internal Walls and Masses	Window & Solar	Mech. supply air	Infiltration & Openings	Occupants	Equipment	Lighting	Local heating units	Local cooling units	Net losses
											
1	-25143.9	-30.7	-8174.7	-1851.9	-1312.5	1307.8	1424.1	2979.0	29729.2	0.0	1067.3
2	-20481.8	-84.9	-5368.5	-1700.0	-1161.0	1146.6	1238.4	2590.5	22851.8	0.0	963.7
3	-21221.3	-202.0	-3585.5	-1953.6	-1136.8	1264.5	1362.3	2850.0	21552.3	0.0	1066.0
4	-14153.2	-445.3	-32.3	-2128.1	-766.7	1222.2	1300.3	2720.3	11251.5	0.0	1028.7
5	-10775.8	-934.2	2549.5	-2724.2	-576.5	1332.3	1424.2	2979.0	5667.8	0.0	1056.2
6	-7774.2	-555.8	3127.5	-2952.7	-330.5	1186.9	1300.3	2720.3	2258.6	0.0	1017.7
7	-5376.8	-469.6	3909.1	-4510.1	-234.4	1034.0	1361.9	2849.2	402.7	0.0	1032.6
8	-7188.6	945.9	1443.2	-3495.5	-230.3	1311.7	1424.2	2979.0	1755.2	0.0	1045.9
9	-9785.3	810.2	-194.4	-2181.2	-570.6	1202.5	1238.5	2591.2	5854.3	0.0	1027.7
10	-15091.9	490.2	-3126.6	-2143.4	-762.3	1354.8	1424.3	2979.8	13803.8	0.0	1063.7
11	-17524.4	-13.4	-4987.5	-1892.0	-1157.3	1287.3	1362.3	2850.0	19036.4	0.0	1031.7
12	-24472.9	329.7	-8432.1	-1664.2	-1461.4	1201.9	1300.3	2720.3	29402.8	0.0	1069.6
Total	-178990.1	-159.9	-22872.3	-29196.9	-9700.4	14852.4	16161.2	33808.7	163566.4	0.0	12470.8
During heating (MIXED h)	-150058.8	15988.6	-42687.3	-11744.0	-8176.5	5912.3	6354.6	11726.7	163571.7	0.0	9070.8
During cooling (MIXED h)	-22957.0	-16536.9	20134.5	-15141.3	-1122.9	7138.2	7905.2	17976.5	0.0	0.0	2610.0
Rest of time	-5974.3	388.4	-319.5	-2311.6	-401.0	1801.9	1901.4	4105.5	-5.3	0.0	790.0

Table 5 illustrates that the envelope and thermal bridges along with the windows are responsible for the main heat losses during heating. During the cooling, the window & solar part together with lighting are responsible for the main heat gain.

Table 6. Envelope heat transmission (kWh).

Month	Walls	Roof	Floor	Windows	Doors	Thermal bridges
						
1	-17657.8	-521.4	-454.2	-9190.4	0.0	-6511.2
2	-14211.1	-438.9	-475.9	-7641.7	0.0	-5355.4
3	-14537.2	-418.8	-569.5	-8083.3	0.0	-5695.6
4	-9339.0	-258.8	-544.3	-5927.0	0.0	-4010.7
5	-6859.5	-121.4	-532.9	-5063.4	0.0	-3261.3
6	-4694.7	-26.3	-454.8	-4324.7	0.0	-2598.8
7	-3014.1	53.6	-406.9	-3814.5	0.0	-2009.4
8	-4368.7	-31.6	-312.2	-4083.5	0.0	-2476.4
9	-6378.4	-149.3	-243.8	-4513.2	0.0	-3014.2
10	-10355.4	-317.3	-254.5	-6003.8	0.0	-4164.9
11	-12292.2	-387.2	-306.2	-6508.2	0.0	-4538.4
12	-17055.0	-452.6	-387.5	-9199.5	0.0	-6578.5
Total	-120763.1	-3070.0	-4942.7	-74353.2	0.0	-50214.8
During heating	-101048.8	-3100.0	-4855.6	-52576.7	0.0	-41060.2
During cooling	-15760.5	18.4	-1.4	-17398.9	0.0	-7212.1
Rest of time	-3953.8	11.6	-85.7	-4377.6	0.0	-1942.5

Values shown in Table 6 and Table 5 indicate that during heating, the heat losses through the windows without considering the solar heat gain is -52576.7 kWh, while this value drops to -42687.3 kWh with taking the solar heat gain into consideration. This shows that in the winter, solar heat gain has compensated about 18% of the heat losses through the windows which proves that the solar heat gain plays an important role in heating demand reduction. During cooling, without considering the solar heat gain, about -17398.9 kWh heat is lost through the windows, while with considering the solar heat gain, the heat loss of -17398.9 kWh will be converted to the heat gain of 20134.5 kWh. This indicates that the solar heat gain in the summer can contribute to increasing the need for cooling, thereby raising the energy usage.

4.1.2 Thermal comfort

The following tables show the data regarding thermal comfort based on Fanger's comfort indices and EN-15251 standard for the four selected zones. According to category II (normal level of thermal comfort expectation) defined in the EN-15251 standard, PPD should be less than 10 %, so the months in which PPD is more than 10% are considered as uncomfortable months. More detailed information regarding the EN-15251 standard and simulation results for thermal comfort can be found in Appendix A and Appendix E respectively.

Table 7. Thermal comfort data based on EN-15251 standard for the selected zones without the window films (case A)

Zone	Number of occupancy hours based on comfort category				Number of occupants	Number of equipment units
	Best	Good	Acceptable	Unacceptable		
4	1074	2756	2898	234	3	3
14	1007	2797	2925	207	2	2
44	1542	1745	1822	1310	8	8
56	961	2535	2667	465	2	2

Table 8. Fanger's comfort indices for uncomfortable months for the selected zones without films

zone	Uncomfortable months	Variables		
		PPD, % (Predicted percentage dissatisfied)	PMV (Predicted mean vote)	Average operative temperature (°C)
4	July	11.46	0.42	27.15
14	July	11.12	0.40	26.80
44	June	15.02	0.49	27.87
	July	26.51	0.73	29.82
	August	20.13	0.61	28.46
56	July	15.88	0.51	27.96

Table 9. Building comfort reference in case A (without films).

Percentage of hours when operative temperature is above 27°C in worst zone	42 %
Percentage of hours when operative temperature is above 27°C in average zone	18 %
Percentage of total occupant hours with thermal dissatisfaction	13 %

Zone 4

According to Table 7, thermal comfort in zone 4, for most of the hours is ranked as acceptable and above the acceptable level. The number of unacceptable occupancy hours is 234 which mostly belongs to July. Table 8 indicates that the PPD in July is 11.46 % which is above the limit (10%) specified by the EN-15251 standard, and that is why July was considered as an uncomfortable month. The average operative temperature in July is 27.15 (°C) which is higher than the standard limit. (see Appendix E)

Zone 14

Table 7 shows that thermal comfort in zone 14 for most hours of the year is ranked as acceptable and above that. Table 8 indicates that in July, PPD is 11.12 % and the average operative temperature is 26.8°C which is slightly better than zone 4. For other months, thermal comfort is in compliance with the standard.

Zone 44

Data regarding thermal comfort shows that zone 44 has the worst situation compared to the other zones. The number of unacceptable occupancy hours is 1310 which is five times as large as zone 4 and zone 14. Table 8 shows that the PPD values in June, July and August are 15.02 %, 26.51%, 20.13 % respectively of which July represents the highest PPD. The average operative temperatures for these months are above 27°C which do not comply with the standard level.

Zone 56

According to Table 7, thermal comfort in zone 56, for most of the hours is ranked as acceptable and above that. The number of unacceptable occupancy hours is 465 which mostly belongs to July. Tables 8 also shows that the PPD in July is 15.88 % and the average operative temperature is about 28°C which are all above the standard level. The information regarding the standard level can be found in Appendix A.

Table 9 indicates, in worst zone of the building, for 42 % of the hours the operative temperature is above 27°C, and 13 % of the total occupant hours is ranked as thermally dissatisfied.

4.2 Base model (case A (without window films)) validation

According to Table 4, the delivered energy from district heating is 221872 kWh including the heating and domestic hot water for the whole year. To verify this amount, it should be compared with the energy usage bill of the building, specifically for district heating of course. Table 4-6 collected from “Gavlefastigheter Company” shows the energy usage of the building supplied by district heating. As it is shown in the table, the total amount of the energy usage is 228790 kWh for the whole year. By comparing the result of the simulation and the energy bill, a small difference of 6918 kWh is achieved.

$$Error = \frac{(Simulation\ Results - Reference\ Value)}{Simulation\ Result} = \frac{221872 - 228790}{221872} = 3\% \quad Eq. 6$$

Eq. 6 shows that the error percent is about 3%, and this means that the simulation result is 3% deviant from the amount shown in the energy bill taken as reference. This small deviation is acceptable and it can be concluded that the simulation results are valid.

Table 10. Energy bill for district heating, collected from Gavlefastigheter Company.

Vitec	
District heating (MWh/month)	
2018	
januari	41.31
februari	36.74
mars	34.98
april	21.68
maj	3.45
juni	1.67
juli	0.84
augusti	1.37
september	5.93
oktober	17.16
november	27.68
december	35.99
Total: 228.79	







4.3 Results of the simulation in the presence of low-E films (case B)

The simulation results regarding the energy performance and thermal comfort in the presence of the window films will be discussed separately in the following parts.

4.3.1 Energy performance

The following tables depict the results of the simulation in which the window films were added.

Table 11. Simulated energy use of the building with window films (case B).

		Purchased energy		Peak demand
		kWh	kWh/m ²	kW
	Lighting, facility	33810	22.9	10.8
	Electric cooling	1306	0.9	8.85
	HVAC aux	7057	4.8	2.33
	Total, Facility electric	42173	28.6	
	Fuel heating	202488	137.2	82.23
	Domestic hot water	6324	4.3	0.72
	Total, Facility fuel*	208812	141.5	
	Total	250985	170.1	
	Equipment, tenant	23090	15.7	7.38
	Total, Tenant electric	23090	15.7	
	Grand total	274075	185.7	

*heating value

Table 12. Heat losses for the entire building with window films (case B).

All zones

kWh (sensible only)


















Month	Envelope & Thermal bridges	Internal Walls and Masses	Window & Solar	Mech. supply air	Infiltration & Openings	Occupants	Equipment	Lighting	Local heating units	Local cooling units	Net losses
											
1	-25168.7	-38.1	-5436.8	-1861.8	-1312.7	1308.0	1424.2	2979.7	27032.3	0.0	1067.2
2	-20480.4	-83.7	-3552.4	-1690.7	-1160.4	1147.0	1238.6	2591.3	21022.4	0.0	963.8
3	-21177.0	-152.4	-2340.8	-1920.2	-1137.4	1264.6	1362.3	2850.0	20178.9	0.0	1066.4
4	-14011.4	-381.6	69.8	-2039.7	-766.6	1226.3	1300.3	2720.3	10849.1	0.0	1029.7
5	-10475.4	-773.5	1854.7	-2554.9	-568.4	1363.1	1424.2	2979.7	5690.4	0.0	1058.4
6	-7368.3	-525.2	2287.5	-2740.8	-321.2	1247.4	1300.3	2720.3	2376.7	0.0	1020.5
7	-4940.2	-491.9	2823.6	-4037.5	-228.2	1173.0	1361.9	2849.2	451.1	0.0	1038.0
8	-6992.2	811.9	1080.6	-3311.7	-229.5	1365.4	1424.1	2979.0	1815.4	0.0	1048.2
9	-9694.0	820.0	-75.5	-2127.6	-569.2	1208.6	1238.4	2590.5	5573.2	0.0	1028.5
10	-15073.5	355.5	-2054.4	-2110.4	-761.8	1356.3	1424.2	2979.7	12814.3	0.0	1064.1
11	-17529.1	-14.3	-3313.0	-1893.7	-1158.0	1287.3	1362.3	2850.0	17369.9	0.0	1031.6
12	-24512.6	335.4	-5614.7	-1683.4	-1462.2	1201.9	1300.3	2720.3	26637.9	0.0	1069.4
Total	-177422.8	-137.9	-14271.4	-27972.4	-9675.6	15148.8	16161.4	33810.0	151811.6	0.0	12485.7
During heating (MIXED h)	-150621.6	14212.6	-27403.5	-11807.0	-8220.6	5517.8	5936.9	11359.4	151800.3	0.0	9167.0
During cooling (MIXED h)	-19939.6	-14033.0	12994.5	-13568.6	-1019.5	7455.4	7923.7	17713.5	0.0	0.0	2473.9
Rest of time	-6861.6	-317.5	137.6	-2596.8	-435.5	2175.6	2300.7	4737.1	11.3	0.0	844.8

Table 13. Envelope transmission in the presence of the window films (case B)

Month	Walls	Roof	Floor	Windows	Doors	Thermal bridges
						
1	-17678.3	-522.1	-454.2	-6122.7	0.0	-6513.6
2	-14211.6	-439.2	-475.8	-5092.0	0.0	-5353.9
3	-14500.4	-419.1	-569.4	-5394.1	0.0	-5687.6
4	-9228.8	-258.4	-544.0	-3932.1	0.0	-3980.0
5	-6626.7	-121.6	-532.4	-3315.7	0.0	-3194.7
6	-4389.1	-25.6	-453.9	-2776.6	0.0	-2499.6
7	-2691.3	56.3	-405.1	-2424.7	0.0	-1900.3
8	-4223.6	-30.3	-312.8	-2679.2	0.0	-2425.6
9	-6307.2	-149.4	-244.0	-3006.0	0.0	-2993.0
10	-10344.7	-317.3	-254.6	-4005.3	0.0	-4156.2
11	-12296.3	-387.0	-306.2	-4340.9	0.0	-4539.1
12	-17086.9	-453.8	-387.5	-6133.1	0.0	-6584.7
Total	-119584.9	-3067.5	-4939.9	-49222.3	0.0	-49828.1
During heating	-101492.2	-3100.0	-4861.1	-35226.6	0.0	-41176.5
During cooling	-13540.2	16.9	0.0	-10552.7	0.0	-6415.2
Rest of time	-4552.5	15.6	-78.8	-3443.0	0.0	-2236.4

According to Table 11, the total energy usage of the building for heating and domestic hot water is 208812 KWh for the whole year. Table 12 shows that during heating, the heat loss through windows excluding the solar heat gain is -35226.6 kWh, while this amount by considering the solar heat gain will drop to -27403.5 kWh according to Table 13. This means that to some extent the solar heat gain has compensated for the heat losses through the windows. During cooling the heat which is lost through the windows without considering the solar heat gain is -10552.7 kWh, while by taking the solar heat gain into consideration, this amount will be converted to a heat gain of 12994.5 kWh. The heat gain during cooling means undermining the natural ventilation and more cooling demand, thereby increasing the energy usage.

4.3.2 Thermal comfort

The following tables show the data regarding thermal comfort for the same four zones as selected in section 4.1.2 with the help of Fanger's comfort indices and EN-15251 standard. To make the comparison of the results of case A (without films) and case B (with films) easier, the same uncomfortable months picked for case A, were chosen for case B.

More detailed information regarding the building thermal comfort in the presence of the window films can be found in Appendix E.

Table 14. Thermal comfort data based on EN-15251 standard for the selected zones with the window films (case B)

Zone	Number of occupancy hours based on comfort category				Number of occupants	Number of equipment units
	Best	Good	Acceptable	Unacceptable		
4	1164	2848	2974	158	3	3
14	1074	2822	2947	185	2	2
44	1728	1916	2086	1046	8	8
56	1070	2693	2847	285	2	2

Table 15. Fanger's comfort indices for uncomfortable months for the selected zones with films (case B)

zone	Uncomfortable Months	Variables		
		PPD, %	PMV	Average operative temperature (°C)
4	July	8.56	0.35	26.48
14	July	10.07	0.38	26.61
44	June	10.50	0.39	26.90
	July	21.35	0.63	28.94
	August	16.35	0.54	27.82
56	July	11.46	0.42	27.23

Table 16. Building comfort reference in the presence of the window films.

Percentage of hours when operative temperature is above 27°C in worst zone	35 %
Percentage of hours when operative temperature is above 27°C in average zone	14 %
Percentage of total occupant hours with thermal dissatisfaction	11 %

Zone 4

Table 14 shows that the number of unacceptable occupancy hours is 158 and for the rest of the hours, thermal comfort is ranked as acceptable and better than that. Table 15 represents that although the average operative temperature in July is about 26.5°C which is a little high, the PPD still stands in the accepted range (less than 10%).

Zone 14

According to Table 14, the number of the unacceptable occupancy hours is 185 which mostly belongs to July (for more information see appendix E). table 15 indicates that the PPD is very close to 10 % which is the highest allowed percentage according to EN-15251 standard. The average operative temperature is 26.61°C which is a little high.

Zone 44

The number of unacceptable occupancy hours shown in Table 14 is 1046 which is quite larger than the other selected zones. Table 15 also shows that the unacceptable occupancy hours are mostly related to June, July and August having PPD of 10.5 %, 21.35 % and 16.35 % respectively. The average operative temperature in July is very close to 29°C which represents the most uncomfortable month of the year.

Zone 56

As it is shown in table 14, the number of the unacceptable occupancy hours is 285 mostly related to July, and for the rest of the hours, thermal comfort is ranked as acceptable and even better than that. The PPD in July is 11.46 % exceeding the largest allowed percentage (10 %) and the average operative temperature in July is 27.23°C which is relatively high.

Table 16 shows that, in worst zone of the building, for 35 % of the hours the operative temperature is above 27°C and 11 % of the total occupant hours is ranked as thermally dissatisfied.

4.4 Comparison of the results

In this section the results of the simulation for case A (without films) and case B (with films) will be compared with each other.

4.4.1 Energy performance

Table 17 shows that the total energy use of the building for heating purpose and domestic hot water without window films is 221872 kWh, while this amount in the presence of the window films has decreased to 208812 kWh. It means that the window films have contributed to a 13060 kWh (almost 6%) reduction in the building's annual energy usage for heating and domestic hot water. The amount of energy savings due to the application of the window films regarding electric cooling, lighting, HVAC system and equipment is quite negligible.

Table 17. Energy usage comparison between base model (case A without films) and case B (with window films)

		basemodelN		window fil	
		kWh	kWh/m ²	kWh	kWh/m ²
	Lighting, facility	33809	22.9	33810	22.9
	Electric cooling	1314	0.9	1306	0.9
	HVAC aux	7093	4.8	7057	4.8
	Total, Facility electric	42216	28.6	42173	28.6
	Fuel heating	215548	146.1	202488	137.2
	Domestic hot water	6324	4.3	6324	4.3
	Total, Facility fuel*	221872	150.3	208812	141.5
	Total	264088	178.9	250985	170.1
	Equipment, tenant	23087	15.6	23090	15.7
	Total, Tenant electric	23087	15.6	23090	15.7
	Grand total	287175	194.6	274075	185.7

*heating value

Table 18. Comparison of heat losses for case A (without films) and case B (with films) during heating

kWh

Case	Envelope & Thermal bridges	Internal Walls and Masses	Window & Solar	Mech. supply air	Infiltration & Openings	Occupants	Equipment	Lighting	Local heating units	Local cooling units	Net losses
window fil	-150621.6	14212.6	-27403.5	-11807.0	-8220.6	5517.8	5936.9	11359.4	151800.3	0.0	9167.0
basemodelN	-150058.8	15988.6	-42687.3	-11744.0	-8176.5	5912.3	6354.6	11726.7	163571.7	0.0	9070.8

Table 19. Comparison of heat losses and heat gains for case A (without films) and case B (with films) during cooling

kWh

Case	Envelope & Thermal bridges	Internal Walls and Masses	Window & Solar	Mech. supply air	Infiltration & Openings	Occupants	Equipment	Lighting	Local heating units	Local cooling units	Net losses
window fil	-19939.6	-14033.0	12994.5	-13568.6	-1019.5	7455.4	7923.7	17713.5	0.0	0.0	2473.9
basemodelN	-22957.0	-16536.9	20134.5	-15141.3	-1122.9	7138.2	7905.2	17976.5	0.0	0.0	2610.0

Table 18 indicates that during heating, the application of the window films has helped to reduce the amount of heat losses through the windows (including solar gain) by almost 36%.

Table 18 also shows that during heating, the heat gain through internal walls and masses in case B (with the window films) is smaller than case A (without films) which could be due to the fact that in the presence of the window films less solar heat is gained by the building (see Tables 5 and 6 for case A and also Tables 12 and 13 for case B).

As it is shown in Table 19, during cooling, with the help of window films, the amount of heat gains through the windows (including solar gain) has dropped by almost 35%.

It can also be seen that during cooling, in case B (with window films) less heat is absorbed by internal walls and masses than case A (without window films) and it could be due to the fact that in case A (without window films), inside of the building is warmer than case B (with films), therefore more heat is absorbed by internal walls and masses in order to cool the building (see Tables 5 and 6 for case A, and also Tables 12 and 13 for case B). More information about each category shown in Tables 18 and 19 can be found in appendix F.

4.4.2 Thermal comfort

In this section the results of thermal comfort for case A (without films) and case B (with films) will be compared with each other.

Table 20. Comparison of thermal comfort in case A (without films) and case B (with films)

zone	Number of unacceptable occupancy hours	
	Without films (Case A)	With films (Case B)
4	234	158
14	207	185
44	1310	1046
56	465	285

Table 21. comparison of Fanger's comfort indices in case A (without films) and case B (with films)

Zone	Uncomfortable Months	PPD, % (Predicted percentage dissatisfied)		Average operative temperature (°C)	
		Without films (Case A)	With films (Case B)	Without films (Case A)	With films (Case B)
4	July	11.46	8.56	27.15	26.48
14	July	11.12	10.07	26.80	26.61
44	June	15.02	10.50	27.87	26.90
	July	26.51	21.35	29.82	28.94
	August	20.13	16.35	28.46	27.82
56	July	15.88	11.46	27.96	27.23

Table 22. Comparison of comfort reference

	basemodelN	window fil
Percentage of hours when operative temperature is above 27°C in worst zone	42	35
Percentage of hours when operative temperature is above 27°C in average zone	18	14
Percentage of total occupant hours with thermal dissatisfaction	14	11

Table 20 shows that the application of the window films has improved the thermal comfort in all of the selected zones. Zone 56 has experienced a 39 % reduction in the number of unacceptable occupancy hours which is the largest among the selected zones, while the number of unacceptable occupancy hours in zone 14 has only dropped by 9 % which is the lowest among the zones.

As it is shown in Table 21, the predicted percentage dissatisfied (PPD), with the help of window films in all the zones has decreased which indicates an improvement in thermal comfort.

The largest reduction in PPD belongs to zone 44 in July which about 5.1 %, and the lowest reduction in PPD is for zone 14 in July. It can be seen that the window films have contributed to some reduction in the average operative temperatures of all the zones. The largest reduction in the operative temperature belongs to zone 44 specifically in June and July, while the lowest reduction belongs to zone 14 in July. It can be said that zone 14 has received the lowest benefit from window films compared to the other zones.

According to Table 22, the percentage of total occupant hours with thermal dissatisfaction has dropped from 14 to 11 with the help of window films.

4.5 Cost analysis

As it is mentioned in part 4.4, the amount of energy saving related to district heating by application of the low-E window films is about 13060 kWh. It is good to repeat that, to focus on the district heating part, the very small difference in the amount of electricity usage between case A (without films) and case B (with films) is excluded from the calculation. To be able to accomplish the cost analysis, the data regarding the window film price, installation cost and district heating price are collected from different sources.

The cost of the tested films calculated by the Swedish installers, “Sunstop”, is 2000 SEK/m² + 150 SEK for each window. The district heating price according to (Ahmed, 2017) is considered 0.65 SEK/kWh. The calculation of the maximum payback period is as follows:

Total number of windows: 76 Area for each window: 2.934 m²

Total window area:

$$76 * 2.934 = 222.984 \text{ m}^2 \quad \text{Eq. 7}$$

Total investment:

$$222.984 * 2000 \text{ SEK} + (76 * 150) = 457368 \text{ SEK} \quad \text{Eq. 8}$$

Saving in district heating energy use:

$$215548 - 202488 = 13060 \text{ kWh/year} \quad \text{Eq. 9}$$

Domestic hot water is excluded because it was the same for the both cases.

Saving cost per year:

$$13060 * 0.65 = 8489 \text{ SEK/year} \quad \text{Eq. 10}$$

Payback period without any interest:

$$(457368)/(8489) = 53.9 \text{ years} \quad \text{Eq. 11}$$

According to Eq. 10, the payback period is very long.

Discounted Payback Period (DPP):

Assuming the discount rate of 1.8 %, the discounted payback period exceeds 100 years which usually does not attract the investors when it comes to profitability.

$$\text{Discounted Payback Period} = \frac{-\ln\left(1 - \frac{457368}{8489} \times 0.018\right)}{\ln(1 + 0.018)} > 100 \text{ years} \quad \text{Eq.12}$$

5 Discussion

In this chapter the results of case A (without window films) and case B (with window films) will be compared against each other from three different perspectives including “energy saving”, “thermal comfort” and “cost saving”.

5.1 Energy saving

The results in chapter 4 have shown an improvement in the annual energy efficiency of the building. Table 17 shows that with the help of the window films, the building’s annual energy usage for heating and domestic hot water, has decreased by almost 6%.

In the literature review chapter, it was mentioned that low-E window films, in the winter can reduce the heat losses through windows by blocking the inside radiative heat from leaving the building. The results of Table 18 have also confirmed this claim. It can be seen that during heating, the application of the low-E window films caused the amount of heat losses through the windows including (solar gain) to reduce by 36 % resulting in energy usage reduction.

It was also discussed that in the summer the low-E window films could send back some part of the solar radiation to the outside of the building and prevent it from getting into the room, thereby avoiding excessive heat gain in the building. The results of Table 19 approve this explanation. According to the results, during cooling, with the help of the window films, the amount of heat gain through windows (including solar gain) has dropped by almost 35 % resulting in better thermal comfort and a slight reduction in cooling demand.

The above-mentioned paragraphs explained how the low-E window films contributed to the reduction in the building’s energy usage, but it should be emphasized that to calculate the total energy savings due to the application of the window films, the results shown in Table 17 should be taken into consideration, because this table shows the results of the one-year simulation based on the climate file, while the results of the cooling and heating simulation shown in Table 18 and 19 are based on synthetic temperatures.

5.2 Thermal comfort

The comparison between the results of case A (without films) and case B (with films) shows that, in the presence of the low-E window films, the thermal comfort in all the selected zones (zones 4, 14, 44 and 56) has improved. According to Table 20, among the selected zones, zone 56 experienced a 39 % reduction in the number of unacceptable occupancy hours which was the largest and zone 14 experienced the lowest reduction in the number of unacceptable occupancy hours which was around 9 %. As far as the predicted percentage dissatisfied (PPD) for uncomfortable months is concerned, zone 56 and zone 44 have benefited from the window films application the most, in a way that on average their PPDs dropped by 4.5 %. Zone 14

has experienced the lowest reduction in PPD during July which was about 1 % (see Table 21).

As it is shown in Table 21, the window films have helped to reduce the operative temperatures during the uncomfortable months in all the zones. The largest reduction belongs to zone 44 which is close to 1 °C.

It should be taken into consideration that in both cases (without films and with film), the thermal comfort in July, was the weakest that is why it was considered as the uncomfortable month. Among the selected zones, zone 44 showed the weakest thermal comfort which could be due to having more occupants, equipment and windows.

One thing that could be considered in the simulation is that in Sweden, occupants are usually on holidays in July. This means that in July, the number of occupants of the building could be considered less than the other months which would result in better thermal comfort. In this report due to a lack of information about the number of people working in July, it was assumed that in July, the number of the occupants is the same as the other months, that is why the operative temperature in July is relatively high.

To conclude, in the summer, for all the selected zones even in case B (with window films), during some hours the operative temperatures are relatively higher than the comfort range, and this fact indicates that the solar heat gain control in the summer still needs improving.

5.3 cost saving

The results of section 4.5 show a long-time payback period which is a disadvantage. As it is mentioned before, the price of this window film is relatively high which can lead to a large initial investment cost. In fact, the amount of money saved by the energy use reduction does not match the huge investment cost. As far as the cost-effectiveness is concerned, the application of the window film is questionable, but it should be taken into consideration that for cases similar to this historic building with strict retrofit regulations, finding an alternative for energy efficiency and thermal comfort improvement is not a simple task.

6 Conclusion

6.1 Study results

This research tried to figure out to what extent the application of the low-emissivity window films contributes to the energy usage reduction of a historic stone building. As discussed in the previous chapters, application of the tested low-emissivity window films to some extent has helped to prevent the inside radiative heat from escaping the building which resulted in a 36 % heat loss reduction in the winter. Also, in the summer, the window films participated in a 35% solar gain reduction resulting in better thermal comfort. In addition to the energy savings, the window films contributed to thermal comfort improvement which could be beneficial to all the building's occupants. The percentage of total occupant hours with thermal dissatisfaction has dropped from 14 % (without films) to 11% (with films).

From the cost analysis, it was discovered that the payback period for investing in the window films was very long which was considered as a disadvantage. Other possible problems associated with the window films include bubbles emergence on the films and a reduction in sunlight gains.

By considering the above-mentioned advantages and disadvantages of the window film, this research concludes that for this historic commercial building and other similar buildings in cold climate with strict retrofit regulations, if cost-effectiveness is not prior than thermal comfort and energy efficiency, application of the window films is among the recommendable measures, but not necessarily the best.

6.2 Outlook

The results of this research could be further improved by application of other types of window films and high-tech windows to different types of buildings including both residential and commercial in different climates. Investigation of the effects of outdoor shading on performance of window films, running energy simulation with other programs than IDA ICE, prolongation of the simulated period to several years are some of the for further studies.

6.3 Perspectives

Nowadays, the term “sustainability” has attracted the highest attention than ever. The three pillars of this term include environment, social and economic which all of them play important roles in our life. Currently, environmental degradation is one of the big global issues which has concerned many people around the world. Many contributors to environmental issues have been introduced so far, but fossil fuels consumption stands out from them. Thanks to the growing awareness of fossil fuels’ environmental consequences, the efforts into transformation to renewable and greener sources of energy have accelerated.

In addition to this crucial transformation, other energy saving measures including industrial and buildings’ energy usage reduction, adoption of the latest energy technology, improving the energy behavior, etc. should be carried out. This research has tried to participate in the buildings’ sector energy performance improvement, to have a small role in the environment preservation.

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Appendix A

Standard (EN15251) important tables regarding thermal comfort

Table 23. Examples of recommended categories for design of mechanical heated and cooled buildings.

Category	Description
I	High level of expectation, recommended for spaces occupied by very sensitive and fragile persons with special requirements, like the disabled, the sick, very young children, and the elderly.
II	Normal level of expectation should be used for new buildings and renovations.
III	An acceptable, moderate level of expectation may be used for existing buildings.
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year.

Table 24. four main categories in EN-15251 standard with their PPD and PMV range

Category	Predicted Percentage of Dissatisfied	Predicted Mean Vote
I	<6%	$-0.2 < PMV < 0.2$
II	<10%	$-0.5 < PMV < 0.5$
III	<15%	$-0.7 < PMV < 0.7$
IV	>15%	$PMV < -0.7$ or $PMV > 0.7$

Table 25. Temperature ranges for hourly calculation of cooling and heating energy in three categories of indoor environment

Type of building or space	Category	Temperature range for heating, °C	Temperature range for cooling, °C
		Clothing ~ 1,0 clo	Clothing ~ 0,5 clo
Residential buildings, living spaces (bed room's living rooms etc.) Sedentary activity ~1,2 met	I	21,0 -25,0	23,5 - 25,5
	II	20,0-25,0	23,0 - 26,0
	III	18,0- 25,0	22,0 - 27,0
Residential buildings , other spaces (kitchens, storages etc.) Standing-walking activity ~1,5 met	I	18,0-25,0	
	II	16,0-25,0	
	III	14,0-25,0	
Offices and spaces with similar activity (single offices, open plan offices, conference rooms, auditorium, cafeteria, restaurants, class rooms, Sedentary activity ~1,2 met	I	21,0 – 23,0	23,5 - 25,5
	II	20,0 – 24,0	23,0 - 26,0
	III	19,0 – 25,0	22,0 - 27,0
Kindergarten Standing-walking activity ~1,4 met	I	19,0 – 21,0	22,5 - 24,5
	II	17,5 – 22,5	21,5 – 25,5
	III	16,5 – 23,5	21,0 - 26,0
Department store Standing-walking activity ~1,6 met	I	17,5 – 20,5	22,0 - 24,0
	II	16,0 – 22,0	21,0– 25,0
	III	15,0 – 23,0	20,0 - 26,0

Table 26. Examples of recommended design values of the indoor temperature for design of buildings and HVAC systems

Type of building/ space	Category	Operative temperature °C	
		Minimum for heating (winter season), ~ 1,0 clo	Maximum for cooling (summer season), ~ 0,5 clo
Residential buildings: living spaces (bed rooms, drawing room, kitchen etc) Sedentary ~ 1,2 met	I	21,0	25,5
	II	20,0	26,0
	III	18,0	27,0
Residential buildings: other spaces: storages, halls, etc) Standing-walking ~ 1,6 met	I	18,0	
	II	16,0	
	III	14,0	
Single office (cellular office) Sedentary ~ 1,2 met	I	21,0	25,5
	II	20,0	26,0
	III	19,0	27,0
Landscaped office (open plan office) Sedentary ~ 1,2 met	I	21,0	25,5
	II	20,0	26,0
	III	19,0	27,0
Conference room Sedentary ~ 1,2 met	I	21,0	25,5
	II	20,0	26,0
	III	19,0	27,0
Auditorium Sedentary ~ 1,2 met	I	21,0	25,5
	II	20,0	26,0
	III	19,0	27,0
Cafeteria/Restaurant Sedentary ~ 1,2 met	I	21,0	25,5
	II	20,0	26,0
	III	19,0	27,0
Classroom Sedentary ~ 1,2 met	I	21,0	25,0
	II	20,0	26,0
	III	19,0	27,0
Kindergarten Standing/walking ~ 1,4 met	I	19,0	24,5
	II	17,5	25,5
	III	16,5	26,0
Department store Standing-walking ~ 1,6 met	I	17,5	24,0
	II	16,0	25,0
	III	15,0	26,0

Appendix B

Field Test at Rådhuset “Photos by Magnus Mattsson”

Rådhuset in Gävle

(prepared by Hossein Bakhtiary)



Source: Gavlefastigheter Company

- ▶ Three-storey stone building built in 1784-1790.
- ▶ Located in relatively cold climate.
- ▶ Currently used as an office building for municipal staff.
- ▶ Totally has 37 offices and a basement.
- ▶ The average floor to ceiling height is 4 meters.
- ▶ Totally has 76 double-glazed windows with wooden frames.

Figure 15. Field test at Rådhuset. Photo by Magnus Mattsson



Figure 16. Instrument installation in Rådhuset. Photo by Magnus Mattsson

"Hotbox"



Figure 17. Hotbox creation, photo by Magnus Mattsson



Figure 18. Window film installation, photo by Magnus Mattsson



Energifilm

Figure 19. Installed window film CC75, photo by Magnus Mattsson

Appendix C

Data regarding occupancy, lighting, equipment and radiators for all the zones

Table 27. Number of occupants in each zone (activity level in MET)

		Number of occupants	Activity Level
Zone 2.Occupant 1	⊗ Occupant	2.0	1.2
Zone 3.Occupant 1	⊗ Occupant	2.0	1.2
Zone 4.Occupant 1	⊗ Occupant	3.0	1.2
Zone 9.Occupant 1	⊗ Occupant	1.0	1.2
Zone 12.Occupant 1	⊗ Occupant	1.0	1.2
Zone 13.Occupant 1	⊗ Occupant	1.0	1.2
Zone 14.Occupant 1	⊗ Occupant	2.0	1.2
Zone 16.Occupant 1	⊗ Occupant	1.0	1.2
Zone 17.Occupant 1	⊗ Occupant	1.0	1.2
Zone 20.Occupant 1	⊗ Occupant	1.0	1.2
Zone 25.Occupant 1	⊗ Occupant	1.0	1.2
Zone 29.Occupant 1	⊗ Occupant	1.0	1.2
Zone 30.Occupant 1	⊗ Occupant	1.0	1.2
Zone 33.Occupant 1	⊗ Occupant	2.0	1.2
Zone 34.Occupant 1	⊗ Occupant	1.0	1.2
Zone 36.Occupant 1	⊗ Occupant	1.0	1.2
Zone 28.Occupant 1	⊗ Occupant	1.0	1.2
Zone 37.Occupant 1	⊗ Occupant	1.0	1.2
Zone 38.Occupant 1	⊗ Occupant	1.0	1.2
Zone 39.Occupant 1	⊗ Occupant	2.0	1.2
Zone 41.Occupant 1	⊗ Occupant	1.0	1.2
Zone 43.Occupant 1	⊗ Occupant	1.0	1.2
Zone 44.Occupant 1	⊗ Occupant	8.0	1.2
Zone 45.Occupant 1	⊗ Occupant	2.0	1.2
Zone 46.Occupant 1	⊗ Occupant	1.0	1.2
Zone 48.Occupant 1	⊗ Occupant	1.0	1.2
Zone 49.Occupant 1	⊗ Occupant	2.0	1.2
Zone 51.Occupant 1	⊗ Occupant	2.0	1.2
Zone 55.Occupant 1	⊗ Occupant	1.0	1.2
Zone 56.Occupant 1	⊗ Occupant	2.0	1.2
Zone 62.Occupant 1	⊗ Occupant	1.0	1.2
Zone 63.Occupant 1	⊗ Occupant	1.0	1.2
Zone 64.Occupant 1	⊗ Occupant	1.0	1.2
Zone 71.Occupant 1	⊗ Occupant	1.0	1.2
Zone 72.Occupant 1	⊗ Occupant	1.0	1.2
Zone 73.Occupant 1	⊗ Occupant	2.0	1.2
Zone 74.Occupant 1	⊗ Occupant	2.0	1.2
Zone 76.Occupant 1	⊗ Occupant	1.0	1.2
Zone 67.Occupant 1	⊗ Occupant	1.0	1.2

Table 28. Data regarding the lighting in each zone

Zones		Units	Power (w)	Zones		Units	Power(w)
Zone 1 Light	© Light	6.0	24.0	Zone 51 Light	© Light	6.0	24.0
Zone 2 Light	© Light	6.0	24.0	Zone 52 Light	© Light	3.0	24.0
Zone 3 Light	© Light	6.0	24.0	Zone 53 Light	© Light	3.0	24.0
Zone 4 Light	© Light	6.0	24.0	Zone 54 Light	© Light	3.0	24.0
Zone 5 Light	© Light	6.0	24.0	Zone 55 Light	© Light	6.0	24.0
Zone 6 Light	© Light	6.0	24.0	Zone 56 Light	© Light	6.0	24.0
Zone 7 Light	© Light	6.0	24.0	Zone 57 Light	© Light	6.0	24.0
Zone 9 Light	© Light	6.0	24.0	Zone 58 Light	© Light	3.0	24.0
Zone 10 Light	© Light	3.0	24.0	Zone 59 Light	© Light	3.0	24.0
Zone 11 Light	© Light	6.0	24.0	Zone 61 Light	© Light	6.0	24.0
Zone 12 Light	© Light	6.0	24.0	Zone 62 Light	© Light	6.0	24.0
Zone 13 Light	© Light	6.0	24.0	Zone 63 Light	© Light	6.0	24.0
Zone 14 Light	© Light	6.0	24.0	Zone 64 Light	© Light	6.0	24.0
Zone 15 Light	© Light	6.0	24.0	Zone 65 Light	© Light	6.0	24.0
Zone 16 Light	© Light	6.0	24.0	Zone 68 Light	© Light	3.0	24.0
Zone 17 Light	© Light	6.0	24.0	Zone 69 Light	© Light	6.0	24.0
Zone 18 Light	© Light	6.0	24.0	Zone 70 Light	© Light	6.0	24.0
Zone 19 Light	© Light	3.0	24.0	Zone 71 Light	© Light	6.0	24.0
Zone 20 Light	© Light	6.0	24.0	Zone 72 Light	© Light	6.0	24.0
Zone 21 Light	© Light	6.0	24.0	Zone 73 Light	© Light	6.0	24.0
Zone 22 Light	© Light	3.0	24.0	Zone 74 Light	© Light	6.0	24.0
Zone 23 Light	© Light	6.0	24.0	Zone 75 Light	© Light	6.0	24.0
Zone 24 Light	© Light	3.0	24.0	Zone 76 Light	© Light	6.0	24.0
Zone 25 Light	© Light	6.0	24.0	Zone 77 Light	© Light	6.0	24.0
Zone 26 Light	© Light	6.0	24.0	Zone 78 Light	© Light	3.0	24.0
Zone 29 Light	© Light	6.0	24.0	Zone 79 Light	© Light	3.0	24.0
Zone 30 Light	© Light	6.0	24.0	Zone 84 Light	© Light	6.0	24.0
Zone 31 Light	© Light	6.0	24.0	Zone 85 Light	© Light	6.0	24.0
Zone 32 Light	© Light	6.0	24.0	Zone 86 Light	© Light	3.0	24.0
Zone 33 Light	© Light	6.0	24.0	Zone 27 Light	© Light	6.0	24.0
Zone 34 Light	© Light	6.0	24.0	Zone 87 Light	© Light	3.0	24.0
Zone 35 Light	© Light	6.0	24.0	Zone 80 Light	© Light	3.0	24.0
Zone 36 Light	© Light	6.0	24.0	Zone 67 Light	© Light	6.0	24.0
Zone 28 Light	© Light	6.0	24.0	Zone 60 Light	© Light	3.0	24.0
Zone 37 Light	© Light	6.0	24.0	Zone 66 Light	© Light	6.0	24.0
Zone 38 Light	© Light	6.0	24.0				
Zone 39 Light	© Light	6.0	24.0				
Zone 40 Light	© Light	6.0	24.0				
Zone 41 Light	© Light	6.0	24.0				
Zone 42 Light	© Light	6.0	24.0				
Zone 43 Light	© Light	6.0	24.0				
Zone 44 Light	© Light	6.0	24.0				
Zone 45 Light	© Light	6.0	24.0				
Zone 46 Light	© Light	6.0	24.0				
Zone 47 Light	© Light	6.0	24.0				
Zone 48 Light	© Light	6.0	24.0				
Zone 49 Light	© Light	6.0	24.0				
Zone 50 Light	© Light	6.0	24.0				

Table 29. Data regarding equipment in each zone, Power (W)

Zones		Units	Power
Zone 2.Equipment	1 © Equipment	2.0	125.0
Zone 3.Equipment	1 © Equipment	2.0	125.0
Zone 4.Equipment	1 © Equipment	3.0	125.0
Zone 9.Equipment	1 © Equipment	1.0	125.0
Zone 12.Equipment	1 © Equipment	1.0	125.0
Zone 13.Equipment	1 © Equipment	1.0	125.0
Zone 14.Equipment	1 © Equipment	2.0	125.0
Zone 16.Equipment	1 © Equipment	1.0	125.0
Zone 17.Equipment	1 © Equipment	1.0	125.0
Zone 20.Equipment	1 © Equipment	1.0	125.0
Zone 25.Equipment	1 © Equipment	1.0	125.0
Zone 29.Equipment	1 © Equipment	1.0	125.0
Zone 30.Equipment	1 © Equipment	1.0	125.0
Zone 33.Equipment	1 © Equipment	2.0	125.0
Zone 34.Equipment	1 © Equipment	1.0	125.0
Zone 36.Equipment	1 © Equipment	1.0	125.0
Zone 28.Equipment	1 © Equipment	1.0	125.0
Zone 37.Equipment	1 © Equipment	1.0	125.0
Zone 38.Equipment	1 © Equipment	1.0	125.0
Zone 39.Equipment	1 © Equipment	2.0	125.0
Zone 41.Equipment	1 © Equipment	1.0	125.0
Zone 43.Equipment	1 © Equipment	1.0	125.0
Zone 44.Equipment	1 © Equipment	8.0	125.0
Zone 45.Equipment	1 © Equipment	2.0	125.0
Zone 46.Equipment	1 © Equipment	1.0	125.0
Zone 48.Equipment	1 © Equipment	1.0	125.0
Zone 49.Equipment	1 © Equipment	2.0	125.0
Zone 51.Equipment	1 © Equipment	2.0	125.0
Zone 55.Equipment	1 © Equipment	1.0	125.0
Zone 56.Equipment	1 © Equipment	2.0	125.0
Zone 62.Equipment	1 © Equipment	1.0	125.0
Zone 63.Equipment	1 © Equipment	1.0	125.0
Zone 64.Equipment	1 © Equipment	1.0	125.0
Zone 71.Equipment	1 © Equipment	1.0	125.0
Zone 72.Equipment	1 © Equipment	1.0	125.0
Zone 73.Equipment	1 © Equipment	2.0	125.0
Zone 74.Equipment	1 © Equipment	2.0	125.0
Zone 76.Equipment	1 © Equipment	1.0	125.0
Zone 67.Equipment	1 © Equipment	1.0	125.0

Table 30. Data regarding radiators in each zone

[illegible]

Appendix D

Room height ⓘ

☒ to ceiling m

☐ to roof m

Floor height above ground m

Room height ⓘ

☒ to ceiling m

☐ to roof m

Floor height above ground m

1st floor height 2nd floor height

Room height ⓘ

☒ to ceiling m




☐ to roof m

Floor height above ground m

3rd floor height

Figure 20. Building's floors' height

Table 31. Window film's technical data published by the manufacturer "3M Company"

Glass Type (All 1/4")	Film Type	Visible Light			Total Solar Energy Rejected	Solar Heat Gain Coefficient (G Value)
		Reflected (interior)	Reflected (exterior)	Transmitted		
 Clear	Thinsulate™ 40	10%	7%	36%	59%	0.41
	Thinsulate™ 75	12%	15%	74%	47%	0.53
 Tinted	Thinsulate™ 40	9%	5%	22%	67%	0.33
	Thinsulate™ 75	10%	8%	44%	60%	0.40
 Double Clear	Thinsulate™ 40	11%	14%	32%	54%	0.46
	Thinsulate™ 75	17%	21%	66%	49%	0.51

Number of people in group

[Schedule](#)

Activity level MET [* Schedule smoothing applied.
Change in [System parameters](#)]

[Clothing](#)

☒ Constant ± * CLO

☐ Schedule

[*clothing is automatically adapted
between limits to obtain comfort]

Figure 21. Occupant configuration

Pressure coefficient

Face \ Angle	0	45	90	135	180	225	270	315	Face azi...
Building body									
f1aa	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2	0.0
f1ab	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2	90.0
f1ac	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	0.0
f1b	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2	270.0
f1c	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2	0.0
f2a	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2	90.0
f2b	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2	180.0
f2ca	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2	90.0
f2cb	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2	0.0
f2cc	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2	90.0
f3a	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2	180.0
f3b	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2	270.0
f3ca	0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1	180.0
f3cb	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2	90.0
f3cc	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2	180.0
f4a	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2	270.0
f4b	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2	0.0
f4ca	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2	270.0
f4cb	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2	180.0
f4cc	0.4	0.2	-0.6	-0.5	-0.3	-0.5	-0.6	0.2	270.0
Crawl space	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Roof	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.0

Figure 22. Pressure coefficient input data

Appendix E

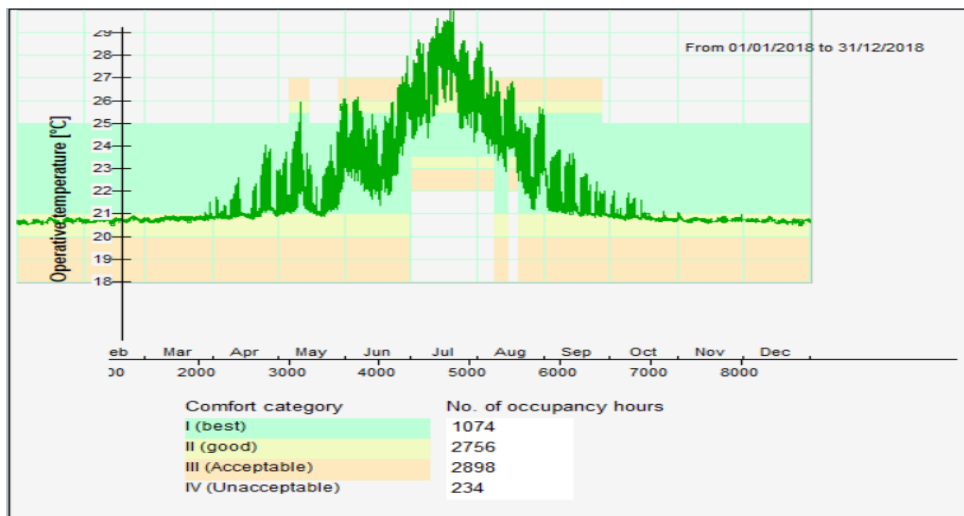


Figure 23. Thermal comfort data based on EN-15251 standard for zone 4 without films

Table 32. Fanger comfort indices for zone 4 without films

	Variables	
	PPD, Predicted Percentage of Dissatisfied, %	PMV, Predicted Mean Vote, (*10)
January	3.395	-0.1571
February	3.131	-0.1422
March	3.062	-0.1364
April	2.575	-0.07792
May	2.638	0.01567
June	3.65	0.1523
July	11.46	0.4201
August	4.932	0.2092
September	2.203	-0.02136
October	2.859	-0.1136
November	3.019	-0.1306
December	3.044	-0.139
mean	3.847	-0.008876
mean*8760.0 h	33696.1	-77.75
min	2.203	-0.1571
max	11.46	0.4201

Table 33. Operative and mean air temperatures for zone 4 without films

	Variables	
	Mean air temperature, Deg-C	Operative temperature, Deg-C
January	21.0	20.67
February	21.0	20.73
March	21.01	20.79
April	21.33	21.25
May	22.19	22.23
June	24.0	24.11
July	27.0	27.15
August	24.39	24.5
September	21.61	21.6
October	21.07	20.88
November	21.0	20.74
December	21.0	20.69
mean	22.23	22.13
mean*8760.0 h	194722.8	193824.6
min	21.0	20.67
max	27.0	27.15

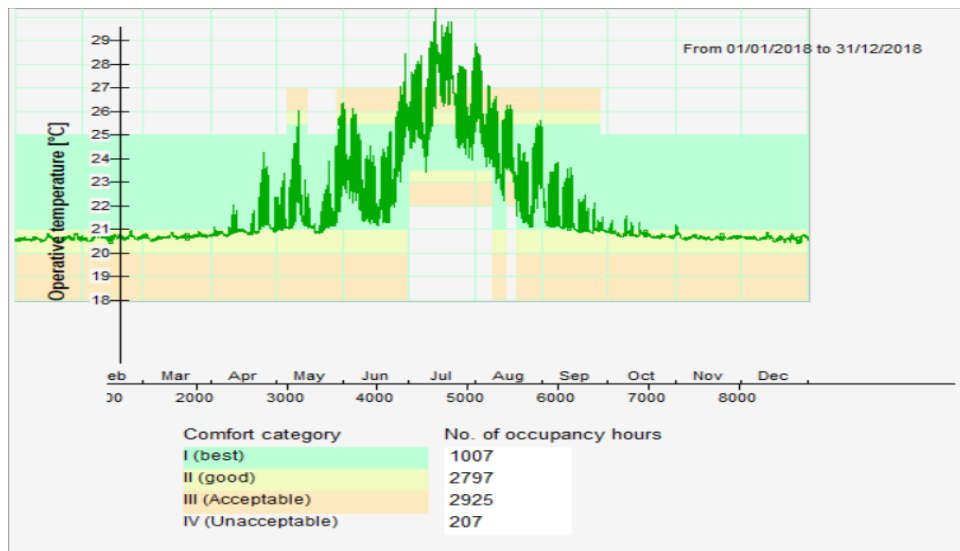


Figure 24. Thermal comfort data based on EN-15251 standard for zone 14 without films

Table 34. Fanger comfort indices for zone 14 without films

	Variables	
	PPD, Predicted Percentage of Dissatisfied, %	PMV, Predicted Mean Vote, (*10)
January	3.367	-0.1552
February	3.116	-0.141
March	3.077	-0.1377
April	2.627	-0.08464
May	2.724	0.002666
June	3.4	0.123
July	11.12	0.4066
August	4.855	0.1993
September	2.234	-0.02639
October	2.876	-0.1161
November	3.006	-0.1297
December	3.027	-0.1378
mean	3.802	-0.01523
mean*8760.0 h	33302.2	-133.4
min	2.234	-0.1552
max	11.12	0.4066

Table 35. Operative and mean air temperatures for zone 14 without films

	Variables	
	Mean air temperature, Deg-C	Operative temperature, Deg-C
January	21.0	20.62
February	21.0	20.67
March	21.0	20.7
April	21.25	21.14
May	21.96	21.99
June	23.37	23.49
July	26.67	26.8
August	24.07	24.16
September	21.51	21.49
October	21.03	20.79
November	21.0	20.68
December	21.0	20.64
mean	22.08	21.94
mean*8760.0 h	193460.7	192231.1
min	21.0	20.62
max	26.67	26.8

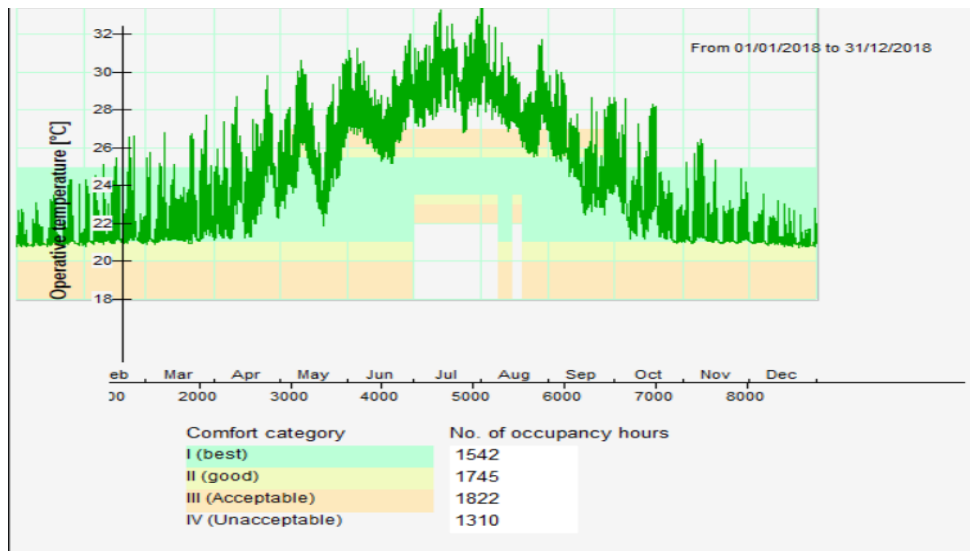


Figure 25. Thermal comfort data based on EN-15251 standard for zone 44 without films

Table 36. Fanger comfort indices for zone 44 without films

	Variables	
	PPD, Predicted Percentage of Dissatisfied, %	PMV, Predicted Mean Vote, (*10)
January	2.721	-0.09041
February	2.501	-0.025
March	2.635	0.01818
April	4.346	0.1555
May	9.121	0.3355
June	15.02	0.4951
July	26.51	0.7378
August	20.13	0.6168
September	6.445	0.258
October	3.486	0.1041
November	2.5	-0.007745
December	2.491	-0.08413
mean	8.218	0.2112
mean*8760.0 h	71986.0	1850.5
min	2.491	-0.09041
max	26.51	0.7378

Table 37. Operative and mean air temperatures for zone 44 without films

	Variables	
	Mean air temperature, Deg-C	Operative temperature, Deg-C
January	21.41	21.3
February	21.82	21.82
March	22.2	22.26
April	23.86	23.96
May	25.89	25.97
June	27.77	27.87
July	29.67	29.82
August	28.34	28.46
September	25.44	25.52
October	23.1	23.16
November	21.92	21.9
December	21.34	21.24
mean	24.41	24.46
mean*8760.0 h	213874.3	214237.1
min	21.34	21.24
max	29.67	29.82

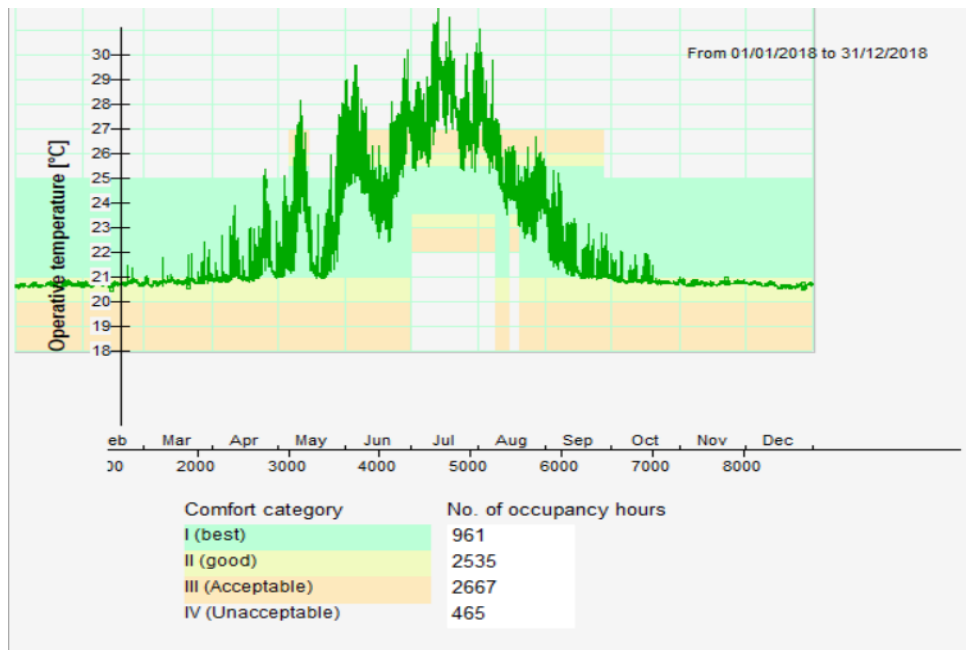


Figure 26. Thermal comfort data based on EN-15251 standard for zone 56 without films

Table 38. Fanger comfort indices for zone 56 without films

	Variables	
	PPD, Predicted Percentage of Dissatisfied, %	PMV, Predicted Mean Vote, (*10)
January	3.411	-0.1582
February	3.137	-0.1425
March	3.007	-0.1313
April	2.53	-0.05734
May	3.595	0.08179
June	7.122	0.2828
July	15.88	0.5175
August	6.973	0.2783
September	2.258	-0.006078
October	2.841	-0.1126
November	3.024	-0.131
December	3.07	-0.1407
mean	4.761	0.02476
mean*8760.0 h	41710.1	216.9
min	2.258	-0.1582
max	15.88	0.5175

Table 39. Operative and mean air temperatures for zone 56 without films

	Variables	
	Mean air temperature, Deg-C	Operative temperature, Deg-C
January	21.0	20.67
February	21.0	20.72
March	21.03	20.84
April	21.51	21.48
May	23.04	23.14
June	25.61	25.77
July	27.77	27.96
August	25.26	25.38
September	21.88	21.92
October	21.08	20.9
November	21.0	20.75
December	21.0	20.67
mean	22.61	22.53
mean*8760.0 h	198088.4	197371.7
min	21.0	20.67
max	27.77	27.96

Case B (with window films)

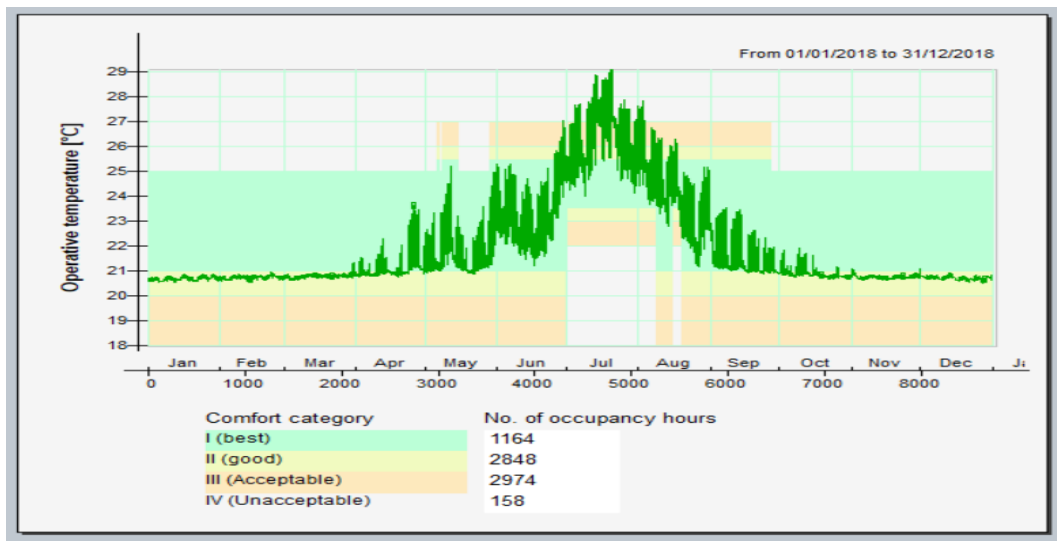


Figure 27. Thermal comfort data based on EN-15251 standard for zone 4 with films.

Table 40. Fanger comfort indices for zone 4 with films

	Variables	
	PPD, Predicted Percentage of Dissatisfied, %	PMV, Predicted Mean Vote, (*10)
January	3.362	-0.1552
February	3.13	-0.1419
March	3.051	-0.136
April	2.607	-0.08504
May	2.505	-0.005606
June	2.972	0.1081
July	8.56	0.348
August	4.238	0.1813
September	2.169	-0.02353
October	2.85	-0.1121
November	2.994	-0.1289
December	3.014	-0.1372
mean	3.465	-0.02293
mean*8760.0 h	30356.8	-200.9
min	2.169	-0.1552
max	8.56	0.348

Table 41. Operative and mean air temperatures for zone 4 with films

	Variables	
	Mean air temperature, Deg-C	Operative temperature, Deg-C
January	21.0	20.69
February	21.0	20.74
March	21.0	20.79
April	21.28	21.19
May	21.95	21.97
June	23.41	23.49
July	26.36	26.48
August	24.12	24.2
September	21.58	21.56
October	21.08	20.91
November	21.0	20.77
December	21.0	20.71
mean	22.08	21.97
mean*8760.0 h	193397.6	192465.0
min	21.0	20.69
max	26.36	26.48

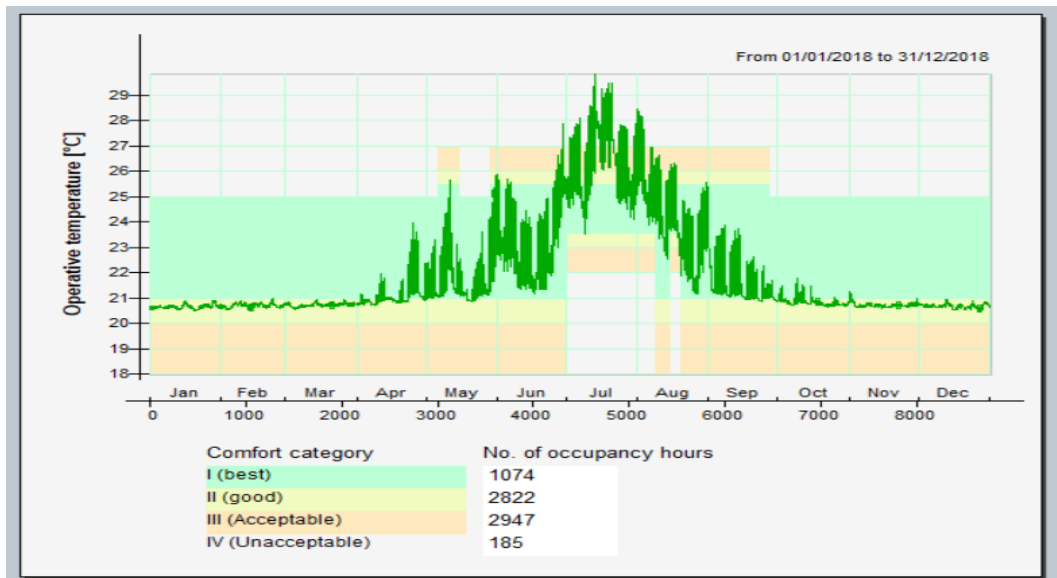


Figure 28. Thermal comfort data based on EN-15251 standard for zone 14 with films.

Table 42. Fanger comfort indices for zone 14 with films

	Variables	
	PPD, Predicted Percentage of Dissatisfied, %	PMV, Predicted Mean Vote, (*10)
January	3.325	-0.1526
February	3.104	-0.1399
March	3.049	-0.1361
April	2.635	-0.0863
May	2.612	-0.004471
June	3.142	0.1107
July	10.07	0.3839
August	4.788	0.2028
September	2.198	-0.01901
October	2.85	-0.1126
November	2.972	-0.1271
December	2.988	-0.1353
mean	3.659	-0.01685
mean*8760.0 h	32049.5	-147.6
min	2.198	-0.1526
max	10.07	0.3839

Table 43. Operative and mean air temperatures for zone 14 with films

	Variables	
	Mean air temperature, Deg-C	Operative temperature, Deg-C
January	21.0	20.65
February	21.0	20.7
March	21.0	20.72
April	21.25	21.13
May	21.89	21.9
June	23.23	23.33
July	26.51	26.61
August	24.17	24.24
September	21.58	21.57
October	21.06	20.84
November	21.0	20.71
December	21.0	20.67
mean	22.07	21.94
mean*8760.0 h	193325.3	192154.7
min	21.0	20.65
max	26.51	26.61

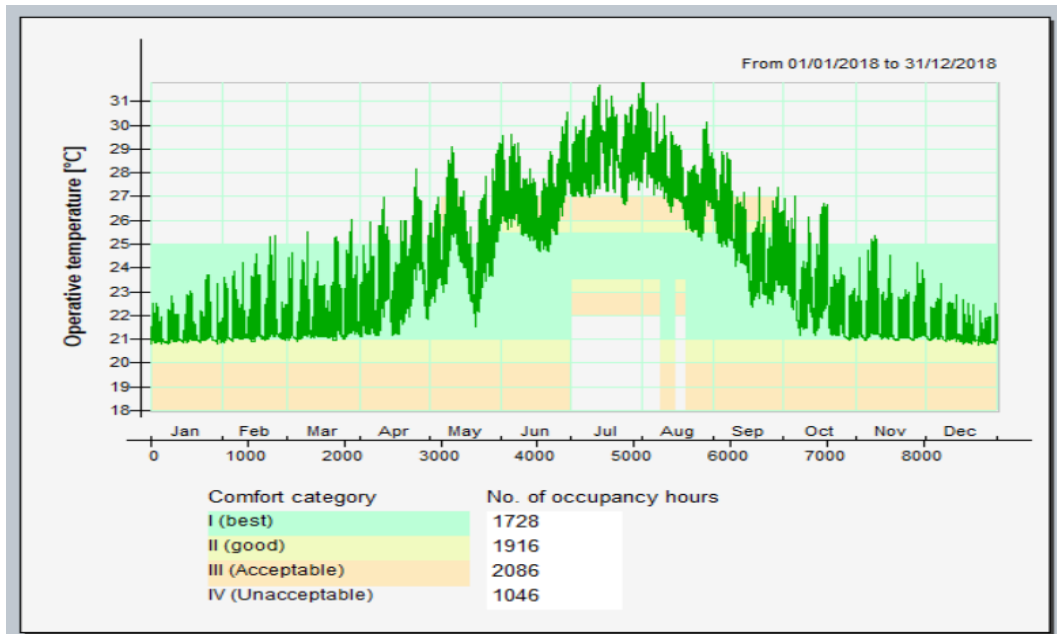


Figure 29. Thermal comfort data based on EN-15251 standard for zone 44 with films.

Table 44. Fanger comfort indices for zone 44 with films

	Variables	
	PPD, Predicted Percentage of Dissatisfied, %	PMV, Predicted Mean Vote, (*10)
January	2.647	-0.08547
February	2.402	-0.03432
March	2.395	-0.004421
April	3.204	0.1009
May	6.063	0.2479
June	10.54	0.3947
July	21.35	0.6322
August	16.35	0.5391
September	5.083	0.2175
October	2.861	0.07316
November	2.39	-0.01182
December	2.419	-0.07643
mean	6.522	0.1676
mean*8760.0 h	57129.3	1468.6
min	2.39	-0.08547
max	21.35	0.6322

Table 45. Operative and mean air temperatures for zone 44 with films

	Variables	
	Mean air temperature, Deg-C	Operative temperature, Deg-C
January	21.45	21.35
February	21.76	21.73
March	21.99	22.02
April	23.27	23.33
May	25.07	25.11
June	26.84	26.9
July	28.83	28.94
August	27.74	27.82
September	24.97	25.02
October	22.8	22.82
November	21.88	21.85
December	21.4	21.31
mean	24.02	24.03
mean*8760.0 h	210382.4	210520.0
min	21.4	21.31
max	28.83	28.94

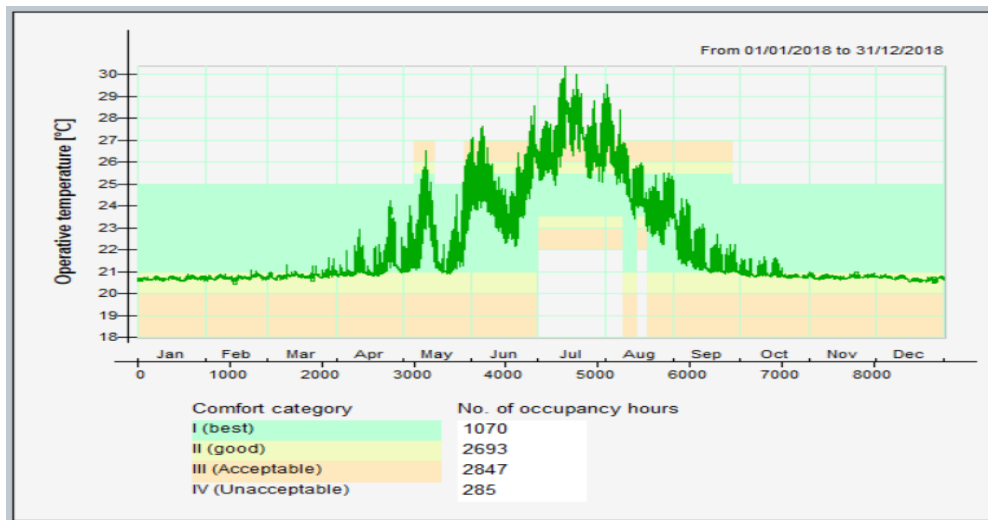


Figure 30. Thermal comfort data based on EN-15251 standard for zone 56 with films.

Table 46. Fanger comfort indices for zone 56 with films

	Variables	
	PPD, Predicted Percentage of Dissatisfied, %	PMV, Predicted Mean Vote, (*10)
January	3.387	-0.1569
February	3.147	-0.1431
March	3.028	-0.1341
April	2.566	-0.07529
May	2.842	0.03094
June	4.512	0.1945
July	11.64	0.4255
August	5.594	0.2359
September	2.19	-0.01556
October	2.86	-0.1141
November	3.008	-0.13
December	3.046	-0.1393
mean	4.002	-5.72E-4
mean*8760.0 h	35053.9	-5.007
min	2.19	-0.1569
max	11.64	0.4255

Table 47. Operative and mean air temperatures for zone 56 with films

	Variables	
	Mean air temperature, Deg-C	Operative temperature, Deg-C
January	21.0	20.68
February	21.0	20.73
March	21.01	20.81
April	21.36	21.3
May	22.48	22.55
June	24.66	24.78
July	27.08	27.23
August	24.87	24.97
September	21.76	21.78
October	21.07	20.89
November	21.0	20.76
December	21.0	20.68
mean	22.37	22.28
mean*8760.0 h	195962.6	195151.5
min	21.0	20.68
max	27.08	27.23

Appendix F

<i>category</i>	<i>comment</i>
Envelope and thermal bridges	Heat gained through external walls, floors, roofs and through thermal bridges.
Internal walls and masses	Heat gained through internal walls, floors, ceilings and internal masses.
External window and solar	Net heat gain through external windows, i.e. through long and short wave radiation as well as via transmission through pane and frame. Advected heat through open windows is included in Infiltration and openings. Note that transmission only is presented in a separate table.
Mechanical supply air	Heat supplied by mechanical ventilation.
Infiltration and openings	Heat supplied via air from leaks and openings. For systems with only mechanical exhaust ventilation, all supply air will be accounted for here.
Occupants	Heat from people in the zone, <i>excluding</i> heat from perspiration.
Equipment	Heat from equipment in the zone, e.g. computers etc.
Lighting	Heat from artificial lighting.
Local heating units	Heat from controlled heating units, e.g. radiators, fan coils etc.
Local cooling units	Heat from controlled cooling units, e.g. chilled beams, fan coils etc.
Net losses	Heat from pipes, ducts etc., the leakage from which has been defined in Extra energy and losses.

Figure 31. Overview and specification of each category used in the IDA ICE simulation report.