CHALMERS

Energy Efficient Windows

Master of Science Thesis in the Master's Programme Structural Engineering and Building Performance Design

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Department of Civil and Environmental Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY

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MASTER'S THESIS 2011:98

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Cover:

Simple picture of a window (www.dreamstime.com)

Chalmers reproservice / Department of Civil and Environmental Engineering, Göteborg, Sweden 2011.

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ABSTRACT

This thesis concerns energy efficient windows in Sweden. In the northern European countries, the cold weather is an important factor to consider. As a result, insulation plays a fundamental role in building construction, preventing or reducing heat loss. Windows are the weakest part of the structures, as the heat flow goes through them easier than through walls. For many years windows have been developed to provide good insulation from temperature and moisture. They can be divided in two well differentiated parts, frame and glass. The first one made of opaque materials and the second one made of transparent materials, in order to fulfil their own function.

The aim of this work is to find the best window in order to reach good rates of energy savings. According to the Swedish building code (BBR), window U-value must be lower than 1 $W/m^2{\cdot}K$ if not a whole heat loss calculation is made for the building. Studies of heat loss were performed in steady-state with the software HEAT2 to find a good value of thermal insulation. Aluminium, PVC and wood were simulated for the frame in combination with different glass cassettes made of two, three or four panes with different mixes of gases in the air gaps. Working as a junction between glass and frame a number of spacers have been tested such as Superspacer, Swisspacer-V or Edgetech. The best option found was a PVC frame with polyurethane foam insulation in its cavities and a 4 pane glass with krypton gas filling in the spaces between the panes and a Swisspacer-V. The U-value obtained for this model was 0.575 $W/m^2{\cdot}K$. This value is reduced by using vacuum or aerogel in the spaces between the panes of the glazing part, especially vacuum filling, because the U-value of the glazing part would be 0.19 $W/m^2{\cdot}K$, while with the krypton gas filling would be 0.279 $W/m^2{\cdot}K$. This glazing filling with vacuum between the panes leads to a total U-value for the window of 0.499 $W/ m^2{\cdot}K$, what means a reduction of more than 13%.

In order to obtain the data necessary for the calculations related to solar radiation, the softwares WINDOW 6.1 and METEONORM were used. Studies were made on the effects of the sun on the inside environment of the building. The purpose of this section was to investigate the energy gain compared to the energy heat loss through a window in Swedish climate. For this reason, the g-values for solar transmission and U-values have been analyzed in order to show the combined effects. Lower U-values lead to better thermal insulation while lower g-values results in less transmission of solar radiation through windows. The analysis was done for two different apartments of 100 m^2, one of them facing north and the other facing south. The results are presented for different seasons of the year.

Following with the work, thermal bridges in the joint between the window and the wall were calculated. For this work the software HEAT 2 was used again. With the models of the windows already designed, the work included the combination of walls and windows to reach the lowest linear thermal transmittance. The best option found was to use a wall with frame insulation and the window located as close as possible to the outside of the building. During this research, windows have also been checked for rain tightness and air tightness.

To sum up, a new concept of window design allows saving energy consumption in our homes and achieves better insulation performance. This is not only important from an economical point of view, it also involves environmental issues.

Key words: Window, frame, glazing, spacer, low-emissivity coats, heat losses, solar radiation, thermal transmittance, thermal bridge, solar heat gain.

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Notations

α	convective surface heat transfer coefficient or absorptivity (-)
τ	transmittance (-)
λ	thermal conductivity (W/m·K)
θ	incidence angle (°)
ρ	density (kg/m3)
σ	Stefan Boltzmann's constant (5,67·10-8 W/m^2·K^4)
Ψ	linear thermal transmittance (W/m·K)
A	area (m^2)
A_f	area of the frame (m^2)
A_g	area of the glass (m^2)
A_{wall}	area of the wall (m^2)
b_g	visible width of glass (m)
b_f	projected width of frame section (m)
b_p	visible width of the opaque panel (m)
b_{wall}	length of the wall (m)
b_{window}	length of the window (m)
d	thickness (m)
d_p	height of the insulation panel (m)
d_{wall}	thickness of the wall (m)
c_p	heat capacity (kJ/kg·K)
d_g	length of the glass (m)
Fi	Inward-flowing fraction of absorbed solar radiation (-)
g	solar gain (-)
I	solar irradiance (W/m^2)
k	thermal conductivity (W/m·K)
L^{2D}	thermal conductance for two dimension heat flow (W/m·K)
L	perimeter or length (m)
Q	net energy transport during the heating season (W)
Q_{window}	net energy transport through the window (W)
Q_{wall}	net energy transport through the wall (W)
Q_{solar}	solar heat gain during the heating season (W)

$Q_{ventilation}$ net energy transport due to ventilation (W)

Q_{supply} net energy required counteracting heat loss (W)

q heat transfer (W/m^2)

q_f heat transfer through the combination of frame and insulation panel (W/m)

q_g heat transfer through the glass (W/m)

R_{se} external surface resistance for horizontal heat flow ($m^2 \cdot K/W$)

R_{si} internal surface resistance for horizontal heat flow ($m^2 \cdot K/W$)

T_i internal temperature (K or °C)

T_s surface temperature (K or °C)

ΔT temperature difference between inside and outside (K or °C)

U thermal transmittance ($W/m^2 \cdot K$)

U_f thermal transmittance of the frame ($W/m^2 \cdot K$)

U_g thermal transmittance of the glass ($W/m^2 \cdot K$)

U_{tot} thermal transmittance of the window ($W/m^2 \cdot K$)

U_p thermal transmittance of the central area of the opaque panel ($W/m^2 \cdot K$)

U_{wall} thermal transmittance of the wall ($W/m^2 \cdot K$)

1 Introduction

1.1 Background

In Northern countries, well-insulation of buildings is important for reducing the energy consumption. Insulating the constructions is one way of reducing heat losses, which means a reduction of the energy use for heating. Different techniques regarding this matter have been developed over the last years

Nowadays, one concept which is taking importance for society is low-energy buildings (Passive house). The main idea of this kind of construction originated from a conversation between Professor Bo Adamson of Lund University, Sweden, and Professor Wolfgang Feist of Institute for Housing and Environment, Germany, in May 1988 (Wikipedia 2011). It is possible to make constructions that do not need any energy supply and produce minimum carbon emissions. As the global warming is increasing and changing our world, we need to slow it down by reducing pollution. So we have to use all knowledge available to reduce our energy consumption, this way the impact on the environment will be lower. The first passive house built in Sweden was in 2001, ten years later than in Germany.

Recently, an experimental project was made in Sweden called "One Tonne Life" (Onetonnelife 2010). The name refers to reduce the global average of carbon dioxide per person today that is about seven to one tonne. These houses are really well-insulated and sealed to consume less energy. Energy consumption is reduced, improving the insulation in walls, roof and foundation, windows and doors. While conventional windows have a U-value around 1.2 $W/m^2{\cdot}K$, windows used in these buildings have a U-value as low as 0.7 $W/m^2{\cdot}K$ in fixed windows and 0.8 $W/m^2{\cdot}K$ in opening windows.

In the Swedish Building Code (BBR), the U-value requirement for windows has been reduced from 2.0 to 1.6 $W/m^2{\cdot}K$ between 1975 and 1985, in an attempt of the government to urge people to build low energy housing. Nowadays, the thermal insulation recommendations stated in the Swedish Building Code (BBR 2006) are used and showed in Table 1 Thermal transmittance according to Swedish Building Code (BBR 2006), only valid if not a whole heat loss calculation is made for the building.

Table 1 Thermal transmittance according to Swedish Building Code (BBR 2006)

Building sections	**For enclosing parts of the building**	**Mainly heated by electrical source**
	U, W/m²·K	U, W/m²·K
Roof	0,13	0,08
Wall	0,18	0,10
Floor	0,15	0,10
Window	1,3	1,1
Outer door	1,3	1,1

Focusing on our subject, the improvement of today's windows plays an important role in this matter. Windows are the weakest part of structures, as the heat flow goes through them easier than through walls, that is why this study has to be thorough. They have been developed for years to get a good insulation from temperature and moisture.

Solar radiation has a big influence on heat transmittance. The solar radiation that comes into the building will depend on the situation of the window but also the glazing takes an important role. Today, double glazing and triple glazing are the most common ones. In Sweden, triple glazing prevails over double glazing due to inherent benefits that it has, such as given extra thermal and acoustic performance.

Frames are an important matter to consider when evaluating the thermal characteristic of a window. In fact they are one of the most important factors for heat loss. Considering two windows with the same properties but different sizes, the frame will represent a larger proportion of the area in the smaller window than in the larger one. Hence a more substantial part of heat loss will be attributed to the frame in the smaller window than to the frame in the larger window. Swedish standards usually used a square window with size 1200 x 1200 mm until 2009, when they changed to the European dimensions 1230 mm ± 25% x 1480 mm ± 25% according to EN 14351.

1.2 Purpose

The aim of this work is to investigate window designs and techniques available nowadays in Sweden, and to perform the necessary improvements and calculations for optimizing energy efficiency.

The main purpose of this thesis is to examine the effects of using better insulated windows for extreme climates, and its aim is to reach good rates of energy savings. With this work we try to offer an alternative in windows structures to reduce the energy consumption of our buildings. The way to get the target is decreasing the heat transfer between the building indoor and the outside.

Another goal for this work is to investigate the energy gain by solar radiation compare to the energy heat loss through a window in Swedish climate.

In the following chapters, the calculations and improvements performed to reach the goal of the thesis are shown.

1.3 Methodology

The research, analysis and methods broadly will focus on different phases, in which the main work is divided.

In the first step the recognition and annotation of techniques and window designs that are available nowadays is done by reading literature about previous studies related to this topic. Later calculations, using the computer program HEAT2, of U-values are done for different kinds of windows, regarding to the number of glass pieces, gas used between them and frame design are selected.

The next step is to propose improvements for low-energy windows, such as avoiding any heat transmittance between glass and frame or between wall and frame as much as possible. It is also important to figure out how the solar radiation and lighting affect them. This part is accomplished by working with the simulation programs METEONORM and WINDOW6. The following task is to calculate thermal bridges between the window and the wall when they are installed for different combinations. For this work the program HEAT2 is used.

The last part of the thesis focuses on evaluation of drawings of rain and air tightness.

1.4 Outline

Chapter 1: Introduction

The structure and purpose of the thesis is briefly described in this section to facilitate the reading of the following chapters.

Chapter 2: Materials for windows manufacturing

The most common materials used for frames and glazing of well insulated windows are described in this chapter.

Chapter 3: Calculation models for windows

The main purpose of this chapter is to obtain the value of thermal transmittance (U-value) for different configurations of windows. The different models are verified by the software HEAT2 7.1. The evaluations of U-values have been used to design the frame and glazing of the definitive window structure.

Chapter 4: Solar effect optimization in windows

This chapter talks about investigating different improvements for low-energy windows. Solar radiation and lighting have been calculated using the software HEAT2 7.1.

Chapter 5: Models for prediction and estimation of window's positions with respect to wall

In this chapter different values have been calculated of thermal bridges regarding to the position of the window in the external wall. For this work the software HEAT2 7.1 has been used.

Chapter 6: Evaluation of the tightness and installation process.

The main purpose of this section is to evaluate rain and air tightness through drawings. Specifications for installations of well insulated windows.

Chapter 7: Summary and conclusions.

This section presents the main conclusions of the work done in a summarize way.

Chapter 8: References.

Bibliography of the references used during the whole report.

Appendix.

2 Materials for windows manufacturing

A window can be described as an opening in a wall or door that allows the passage of light and, if it's not well closed or sealed, air and sound. Windows are usually made of glazed embedded in a frame.

"Primitive windows were just holes in a wall. Later, windows were covered with animal hide, cloth, or wood. Shutters that could be opened and closed came next. Over time, windows were built that both protected the inhabitants from the elements and transmitted light. The Romans were the first to use glass for windows. In Alexandria ca. 100 CE, cast glass windows, although with poor optical properties, began to appear. Mullioned glass windows were the windows of choice among European well-to-do, whereas paper windows were economical and widely used in ancient China, Korea and Japan. In England, glass became common in the windows of ordinary homes only in the early 17th century where as windows made up of panes of flattened animal horn were used as early as the 14th century in Northern Britain. Modern-style floor-to-ceiling windows became possible only after the industrial glass making process was perfected" (Wikipedia 2010).

In the mid 1970s, USA reached to the conclusion that energy was not unlimited and free. The US Department of Energy calculated that 25% of heating costs in a house were used to countervail the heat loss through the window. Hitherto, most windows were single pane with wooden frame. Manufactures started to use aluminium in order to replace this kind of windows. In 1970s, multi-pane windows appeared. The space between the glasses was filled with inert gasses to improve their insulating properties (i.e. argon or krypton). Since manufacturers realized that aluminium frames had low insulation, in 1980s, they started to produce vinyl and wood-vinyl composite frames and replace metal spacers with foam or plastic reducing the heat loss and condensation. At the end of 1980s, they started to use low-emissivity coat over glasses. New technologies have appeared recently, like glass of a window that turns darker when the heat affects it, preventing solar radiation, and turns transparent when is cold, letting the heat get into the room (Rodríguez 2011).

In this chapter the used materials for windows in Sweden are presented. The most common materials used for frames and glazing, as well as the best techniques for installation of the windows, are also described in this section.

2.1 Window's frames

The most common materials for windows frame nowadays are:

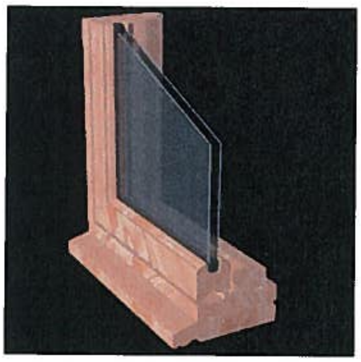
Wood has low thermal conductivity (λ = 0.13-0.18 W/m·K) (EN ISO 10077-2:2003) and good insulation but requires more maintenance than the other options. Wood is an organic and porous material and could rot so these kind of frames need to be treated periodically with paint or sealant. One option is wooden clad windows, creating an exterior face on top of vynil or aluminium that will give the appearance of wood with less maintenance and a weather resistance surface. The inconvenient is that colors are limited for these frames.

Aluminium is one of the least expensive options and durable with minimal maintenance required, making it a popular choice. The main problem of this kind of frames is that the aluminium has high conductivity (λ = 160 W/m·K) and it is not very competitive when it comes to insulation concerns. This effect can be highly reduced with thermal break double or triple glazed.

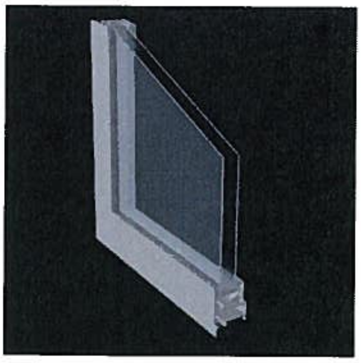
PVC (polyvinyl chloride) frames are easy to maintain, water and storm-proof. These plastics are very energy efficient and own low conductivity (λ = 0.17 W/m·K). The main problem of these materials is that the temperature affects them, producing expansion and contraction of the frame, resulting in cracks, more than in for example wood cases. The best option to minimize the motion is to weld the corners, giving much longer duration.

Fiberglass is less common than the others since it is much more expensive and requires maintenance regularly. On the other hand this material has poor conductivity (λ = 0.40 W/m·K) and the motion will not be a problem but it is still not so competitive in the real market.

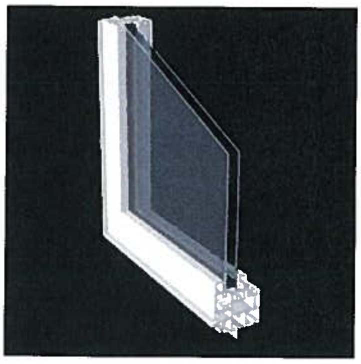
Hybrids give the possibility to combine some of these materials to get better results, e.g. fixed wood and aluminium frame or vinyl and wood. The advantage of this type is the combination of a very good insulating material (wood) and a very good weather resistance one (aluminium or PVC) (U.S. Department of Energy 2011).



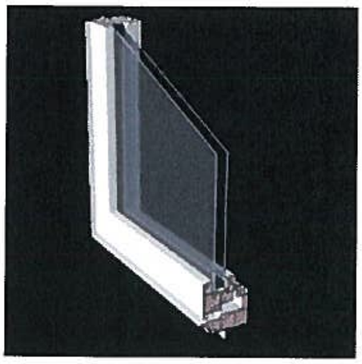
Wood frame



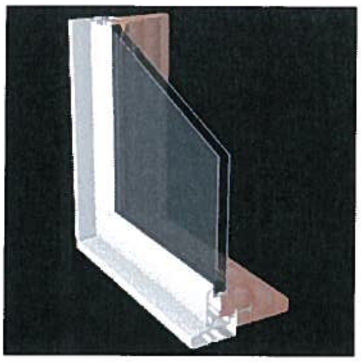
Aluminium frame



PVC frame



Fiberglass frame



Hybrid frame

Figure 1 Materials for window's frames (Center for sustainable building research-University of Minnesota 1998)

2.2 Glazing

The most common materials used for glazing of well insulated windows are: Soda lime glass, PMMA (polymethylmethacrylate), polycarbonates.

Soda-lime glass: It is made of 70% silica (silicon dioxide), 15% soda (sodium oxide), 9% lime (calcium dioxide) and other different compounds in small proportions. Soda lime glass is cheap, reasonable hard, chemically stable and extremely workable. This last feature makes it very useful for manufacturing a wide range of products. The value of its density is 2500 kg/m³, while its thermal conductivity is 1 W/(m·K).

PMMA (polymethylmethacrylate): It is a colourless polymer used for optical applications with composition $C_5H_8O_2$. Its best properties are weatherability and scratch resistance. But it also has weaknesses as low impact strength and poor chemical resistance. Its density is 1180 kg/m³ and its thermal conductivity is 0.18 W/(m·K) (Scott 2001).

Polycarbonates: It is a special type of polyester used as an engineering plastic. Its structure is achieved by reacting bisphenol A with phosgene. Some characteristics are its high impact strength, its transparency and that it can be injection-molded, blow-molded and extruded. This is why it can be used for manufacturing plenty of different products. Its density is 1200 kg/m³ and its thermal conductivity 0.2 W/(m·K) (Scott 2001).

2.2.1 Application of a low emissivity coating

A low-emissivity coating is a very thin metal or metallic oxide layer deposited on the surface of one or more panes of glass. The values of emissivity for different coatings change depending on the number of layers applied and the materials used, such as Bronze, Copper or Silver. It decreases the U-value of the window by reducing the infrared radiation from a warm pane of glass to a colder one. Using low-emissivity coatings that are spectrally selective can avoid the reduction of windows' visible transmittance. A glass without any emissivity coat has an emissivity of 0.90, it can be reduced until values like 0.037 (used in our calculations) or even lowers.

Depending on the climate where the windows are going to be installed, the low-emissivity coating will be applied on different panes. For warm weather it will be employed in the outside pane of glass. On the other hand, if it is desired to keep heat inside the building the layer should be applied in the inside pane of glass (Darling 1999).

The use of this coating increases the prize of the window between 10 and 15%, however energy losses are reduced from 30 to 50% (Darling 1999).

2.3 Other parts of the window

As well as materials mentioned used for frames and glass, others materials have been used for different parts of the window. On the one hand some of them used for insulating the frame are:

Polyurethane foam: It is a polymer consisting of a chain of organic units joined by urethane links. The advantages of this product to use it in the inside of the frame cavities are that it provides insulation and air and vapour barrier at the same time. It has many fields of application not only in construction but in transportation, furniture, packaging etc.

Polyamide 6.6: It is a polymer containing monomers of amides joined by peptide bonds. The principle advantage of polyamide is its extreme durability and strength. Its range of use is very wide also due to its very good performance / cost ratios. In this case it is used to create thermal breaks between different parts of aluminium frames.

EPDM (ethylene propylene diene Monomer): It is an elastomer with ethylene content between 45% and 75%. Higher ethylene content implies higher loading possibilities of the elastomer, better mixing and extrusion. Its main use is for seals and that is its function in the construction of frames. It is employed in the joints between different parts of all the different frames proved.

On the other hand, some materials that have been used to perform the spacer chosen for the calculations (Swisspacer-V) are:

Polysulfide: It is a class of chemical compounds containing chains of sulfur atoms. It is used as a sealant between the glass and the frame of the window. For this function, this material increases the working life of sealants and also controls its mechanical properties in a required direction.

Stainless steel: It is a steel alloy with a minimum of 11% chromium content by mass. With the application of this material stain, corrosion and rust are almost completely avoided. This is applied in the spacer because of its structural properties. It can support very effectively the loads that could appear.

Silica gel: It is a granular, vitreous, highly porous form of silica made from sodium silicate. It is used as a desiccant to fight the possible onset of moisture in the spaces between the panes of the glass.

Styrene acrylonitrile (SAN): It is a copolymer plastic typically made of 70%-80% styrene and 20%-30% acrylonitrile. Its function in the spacers used is containing the silica gel material and it is used because of its good thermal insulation properties.

Butyl rubber: It is a synthetic rubber, a copolymer of isobutylene with isoprene. It is produced by polymerization of about 98% of isobutylene with about 2% of isoprene. It is used as a sealant between the spacer and the panes of the glazing part of the window. Its main properties are flexibility and impermeability.

3 Calculations models for windows

In this section, results obtained from the U-values calculations for different kind of windows are shown. This value is a measure of the heat transmittance due to the difference on temperature between the inside and the outside. It only accounts for heat losses and not for incoming solar radiation.

The U-value of the whole window has been calculated in first term for the frame and in second term for the glazing part of the window. After this, they have been combined so that the value for the entire structure has been obtained. This process is described with drawings to make it easier to understand.

The window's dimensions used to perform calculations of the U-value are specified in Figure 2.

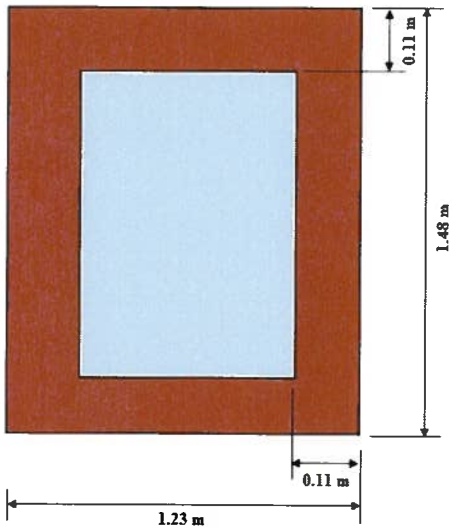


Figure 2 Window's dimensions

To do the calculations, the software HEAT2 7.1 has been used. Values of the heat flow through the structure have been obtained with this program. Taking into account the difference in temperature between the outside and inside of the building, the U-values have been calculated. The software also shows graphic results of the changes on temperatures and heat flow through the window.

3.1 Heat transfer theory

Heat transmittance through a window is not a simple process. It is determined by the radiation and conduction of the different materials and convection between materials used to manufacture the window. The emissivity of a material is the ability of its surface to emit energy by radiation, so it is directly related to this term that will be further treated in Chapter 4. The emissivity has no units because is a ratio between two different energies, one radiated by a particular material and the other one radiated by a black body, both at the same temperature.

Table 2 Thermal conductivities (W/m·K)

Material	**Thermal conductivity (W/m·K)**
Aluminium	160
Steel	50
Softwood	0.13
PVC (rigid)	0.17
EPDM	0.25
Polysulfide	0.40
Silica gel	0.13
Styrene acrynolitrile (SAN)	0.19
Silicone foam	0.12
Butyl rubber (solid)	0.0625
Glass (Soda lime)	1.00
Polyurethane foam	0.03
Air	0.0250
Argon	0.0168
Krypton	0.009
Air(10%) + Ar(90%),outside	0.0198
Air(10%) + Ar(90%),inside	0.02
Air(10%) + Kr(90%)	0.0106
Polyamid (nylon)	0.25

The thermal conductivity is represented by k or λ, and it is the material's ability to conduct heat. The units used for this factor are (W/m·K). In Table 2 it is possible to see the thermal conductivities of the materials used in different kinds of windows.

When the material to be treated is a gas, it will not be enough to consider conductance and radiation but also convection. This is the movement of molecules in the fluids, what means that it cannot happen in solids unless there are pores in the material. For this reason convection has a big influence in heat transfer and therefore it is interesting to avoid it. One way to do it is reducing the cavity where the gas is contained. If the space is small enough convection will not occur. This process has been done for the cavities of frames, so calculations of thermal conductivities have been simplified.

A combination of these three factors has to be considered when the heat transmittance of the whole window is to be calculated. Both parts of the structure, frame and glazing, would be affected by them. In Figure 3 it is possible to observe a graphic representation of these effects.

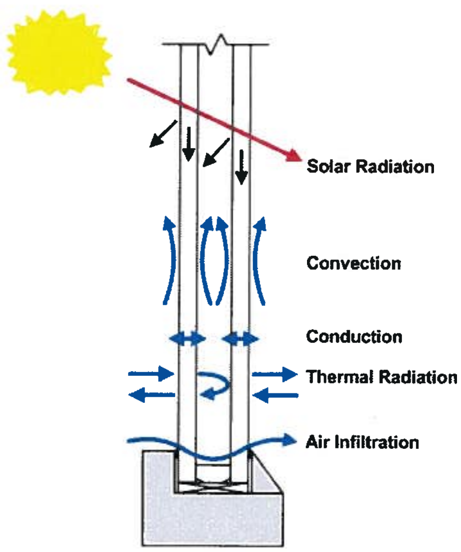


Figure 3 Convection, conduction and radiation (Kent 1999)

Heat transfer takes place by three different mechanisms: conduction, convection and radiation, with the direction of net heat flow always going from the higher temperature to the lower one. A building loses or gains heat by the previously mentioned mechanisms, with the amount of heat transferred by each of them depending on the construction of the building envelope. The building steady-state heat balance can be expressed as:

$$Q_{heating} + Q_{internal\_heat\_gain} = Q_{conduction} + Q_{convection} + Q_{radiation} \quad (1)$$

- Conduction

Heat transfer by conduction refers to the energy that is transferred when vibrating atoms collide and free electrons move collectively. It takes place every time there is a temperature difference between two sides of a material, or two or more different solids in contact. This mode also intervenes when there is heat transferred in gases and liquids and in the contacts between a solid at one side and liquids or gases at the other. The heat transfer rate by conduction though a building component is usually expressed as:

$$Q_{conduction} = U \cdot A \cdot (T_e - T_i)\ (W) \qquad (2)$$

where U ($W/m^2 \cdot K$) is the thermal transmittance of specific building. It includes the thermal resistance of different layers and the surface resistance at both surfaces of the structure. As standard values for energy calculations 0.13 and 0.04 ($m^2 \cdot K/W$ are normally used for the internal and external surface resistances respectively (Hagentoft 2001).

$$U = \frac{1}{R_{si} + \sum \frac{d}{\lambda} + R_{se}} \left(\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}}\right) \qquad (3)$$

A is the material surface area (m^2)

(T_e-T_i) is the temperature difference between the two sides of the material (K)

- Convection

Convection is a mechanism of heat transfer occurring by observable movements of fluids that carry the heat from one place to another. In buildings, this is normally caused by air movements. Fluids expand when they gain heat and contract when they lose heat. Upon expansion, a substance becomes less dense and less subject to gravitational forces, rising and creating a convective current within the fluid and transferring heat, so called natural convection.

The equation used to calculate the convective heat transfer is:

$$Q_{convection} = \alpha \cdot (T_s - T_e)\ \ (\mathrm{W}) \qquad (4)$$

where α is the convective surface heat transfer coefficient and T_s-T_e is the temperature difference between the surface and the ambient air (K)

- Radiation

Radiation refers to heat transfer caused by the emission and absorption of electromagnetic waves. All surfaces above absolute zero emit electromagnetic energy, and when these waves strikes another surface, part of the energy is reflected, part is absorbed and sometimes part can be transmitted, depending on the characteristics of the surface. All these emissions results in heat exchange between surfaces at different temperatures.

In a building, the glass from windows transmits a great part of the energy from the sun (because it is in a shortwave length portion of the infrared range). When the energy enters through the glass, the objects warm up and start to reradiate heat in the long wavelength range as a consequence of their low temperature. Then, this heat is blocked by the glass from the window (because these waves are in the long wavelength range), and as a consequence the temperature inside increases rapidly.

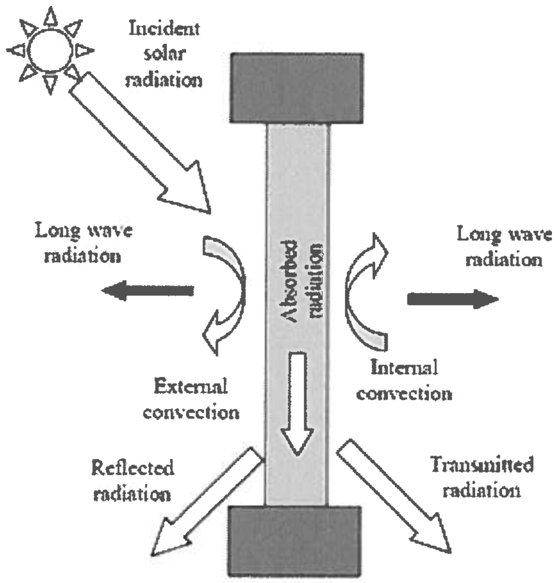


Figure 4 Heat flux over a simple glass window

The amount of solar radiation passing through a window glass can be describes as:

$$Q_{radiation} = (\tau + F_i \cdot \alpha) \cdot I_t \ \text{(W)} \tag{5}$$

The solar gain through a window is the product between the solar heat gain coefficient (g-value) and the total incident solar irradiance in the surface, and can be used to estimate the increase of temperature in an object or space. The solar heat gain coefficient is used in order to calculate the heat loss due to solar radiation and it is represented by the formula shown in equation 6:

$$g = \tau + F_i \cdot \alpha \text{ (-)} \quad (6)$$

τ is the transmittance to radiation (-)

F_i is the inward-flowing fraction of absorbed solar radiation (-). The subscript i refers to individual layers of a fenestration system, where a single pane of glass or a shade constitutes a layer

α is the absorptivity for radiation (-)

The net heat gain through the window will be the difference between the heat gain due to solar radiation and the heat loss through the window, as it is represented in equation 7:

$$Q = g \cdot I_t - U \cdot \Delta T \text{ (W)} \quad (7)$$

3.1.1 Calculation of thermal transmittance

In the beginning of Chapter 3, the dimensions of the two parts of the window were shown. It was divided in two different areas, the frame and the glazing. With those values the areas have been calculated and in Table 3 the results are exhibited.

Table 3 Areas of frame and glazing

Part	**Area (m^2)**
Frame	0.548
Glazing	1.273

The values of these areas have been later used for the calculations of the U-values according to the formulas shown below. The calculations have been made according to the Standard EN ISO 10077-2:2003 (E).

First of all it is presented the formula for the U-value of the area of the frame. It has been calculated with an insulation panel with a thermal conductivity λ_p= 0.035 W/(m·K) as it is shown in Figure 5, according to the standard. The temperatures were considered 20° C in the inside environment and 0°C in the outside. The values for the external surface resistance (R_{se}) and internal surface resistance (R_{si}) were considered 0.04 m^2·K/W and 0.13 m^2·K/W respectively. For the calculations with the software HEAT2, there were used two different values for the internal surfaces resistances (R_{si}), one value of 0.20 m^2·K/W in edges between two surfaces (reduced radiation/convection) and another of 0.13 m^2·K/W for the rest (Normal-Plane surface).

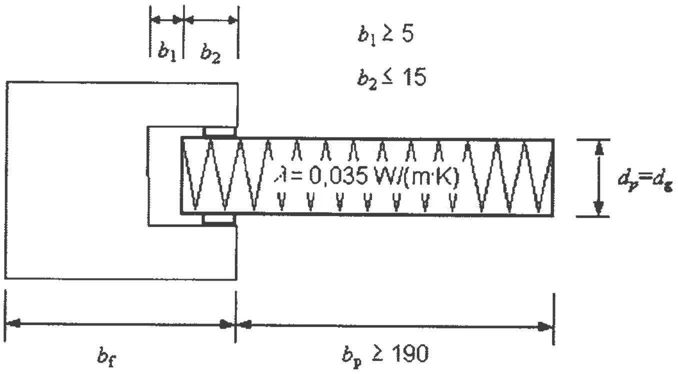


Figure 5 Profile section with panel insulation

$$U_f = \frac{L_f^{2D} - U_p \cdot b_p}{b_f} \tag{8}$$

$$L_{2D} = \frac{q_f}{\Delta T} \tag{9}$$

$$U_p = \frac{1}{R_{se} + R_{si} + \frac{d_g}{\lambda_p}} \tag{10}$$

U_f is the thermal transmittance of the frame section (W/m²·K)

L_f^{2D} is the thermal conductance of the section shown in Figure 4 (W/m·K)

ΔT is the temperature difference between inside and outside (K)

b_f is the projected width of frame section (m)

U_p is the thermal transmittance of the central area of the panel (W/m²·K)

b_p is the visible width of the panel (m)

q_f is the heat transfer through the combination of frame and insulation panel (W/m)

R_{se} is the external surface resistance for horizontal heat flow (m²·K/W)

R_{si} is the internal surfaces resistances for horizontal heat flow (m²·K/W)

d_g is the height of the insulation panel (m)

Next step is to calculate the U-value of the glazing part of the window. The design of the glass has been simulated and the calculation is as shown in equation 11. The calculation of this part has been also calculated by an excel file following EN 673.

$$U_g = \frac{q_g}{\Delta T \cdot d_g} \tag{11}$$

U_g is the U-value of the glass (W/m²·K)

q_g is the heat transfer through the glass (W/m)

d_g is the length of the glass (m)

To calculate the linear thermal transmittance between glass and frame the equation 12 has been used.

$$\Psi = L_{\Psi}^{2D} - U_f \cdot b_f - U_g \cdot b_g \tag{12}$$

Ψ is the linear thermal transmittance between frame and glass (W/m·K)

L_{ψ}^{2D} is the thermal conductance of combination of glass and frame (W/m·K)

b_g is the visible width of the glass (m)

Finally, the U-value of the whole window is calculated following the equation 13.

$$U_{tot} = \frac{U_f \cdot b_f + U_g \cdot b_g - \Psi \cdot L}{A_f + A_g} \tag{13}$$

U_{tot} is the thermal transmittance of the whole window (W/m²·K)

A_f is the area of the frame (m²)

A_g is the area of the of the glass (m²)

L is the perimeter of the joint between glass and frame (m)

3.2 Effects of frame, glazing and spacer on window U-values

The three parts of the window have different functions and also different values for the heat transmittance. The spacer is the element that works as a junction between the frame and the glazing part. It represents a weak point in the structure of the window because through this junction between frame and glass, the low temperatures cross easier than through other parts of the window. For this reason, this specific point has been studied and treated more thoroughly.

On the other hand, the glazing is the strongest part of the window. The materials used for its construction make this section the most resistant to heat transfer through the windows. Thus the higher the ratio between the area of the glass and frame the lower the values of the heat transfer. All this is possible thanks to advances in low-emissivity coating materials used for glazing.

Finally, the frame is the component that presents more possibilities of changes in materials, shapes and dimensions. This is why its design takes longer time than other parts of the window. There is a huge range of different constructions of frames. It has been described before the options for the materials that could be used, but it is very important to focus on the shapes and also the sizes of this element of the window. For this reason several modifications have been made from the original designs, looking for the best option that involves a significant reduction in heat transfer.

To conclude this section, it is important to note that the perfect design of the whole structure is achieved through a judicious combination of the three aforementioned parts. In the next section, these relations between the three components have been deeply studied, simulated by computer monitoring and exposed.

3.3 Modeling of various window frames, spacers and glazing

It has already been said that the Swedish Standards SS-EN ISO 10077-2:2003 have been used for the calculations of U-values. So, it is important to add that the models for different constructions of frames from these standards have been used as well.

It is essential to note that those models from the Swedish Standards have been used as basis for future changes. The most significant modifications have occurred in the dimensions of the internal structural design of the frames, although the changes of different materials have also played an important role on these investigations. All these efforts have been always focused on decreasing the U-value of the whole window.

For the simulations the computer software HEAT2 7.1 has been used. This program has a very simple interpretation of the results thanks to the colour scale used to represent the changes on temperature and heat flows through the structure of the window. Different options allow the user to get further information about the structure treated, e.g. the possibility of increasing the number of cells in order to focus the efforts on a determined area.

On the other hand, the program gives the option to design the user's own constructions, what makes it very easy to change the initial data. However, one remarkable disadvantage is that the drawing tool just lets the user to draw prismatic shapes, which results in a problem when a round surface is needed. The chance of modifying the materials already designed is also a big help for the user, which makes it possible to calculate the same shapes of frames or other parts with different materials very easily.

Two different sizes for glazing have been employed. The first one is made of 3 panes and argon filling with 16 mm spaces thickness and 4 mm panes thickness (total glass thickness 44 mm). The second one is made of 4 panes, krypton filling with 12 mm spaces thickness and 3 mm panes thickness (total glass thickness 48 mm). The length of the glazing part in order to do the calculations was 190 mm and the one for the frame part was 110 mm, as it is shown in the Figure 5.

In the following paragraphs various frameworks and their calculated U-values are presented.

Type 1. To begin, an aluminium frame with several polyurethane foam insulations in its inside cavities is shown. The light green colours represent the insulations and the darker ones indicate frame cavities, what means air in those holes. The insulation material used for the frame inside is polyurethane foam and the thermal breaks represented in dark purple are made of a polyvinyl chloride (PVC). Painted on grey it is shown some junctions made of ethylene propylene diene monomer (EPDM) and one of their functions is to join frame and glass.

Figure 6 Aluminium frame with polyurethane foam insulations

Type 2. The next one is also an aluminium frame, but this time without insulation material in the frame, just with air cavities.

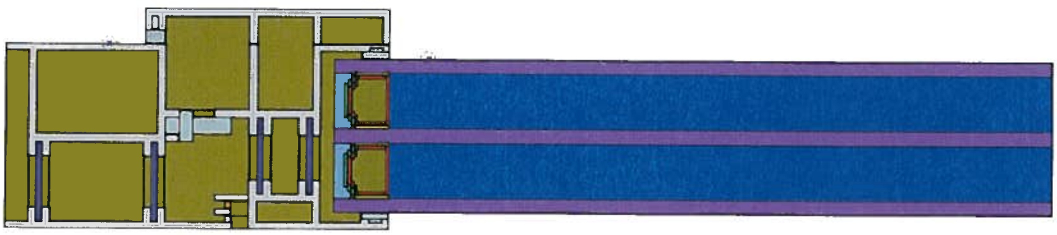


Figure 7 Aluminium frame without polyurethane foam insulations

Type 3. In Figure 8 a frame made of PVC with insulations of polyurethane is shown. The construction properties of PVC allow the manufacturer to divide the frame in small cavities to avoid the effects of convection.

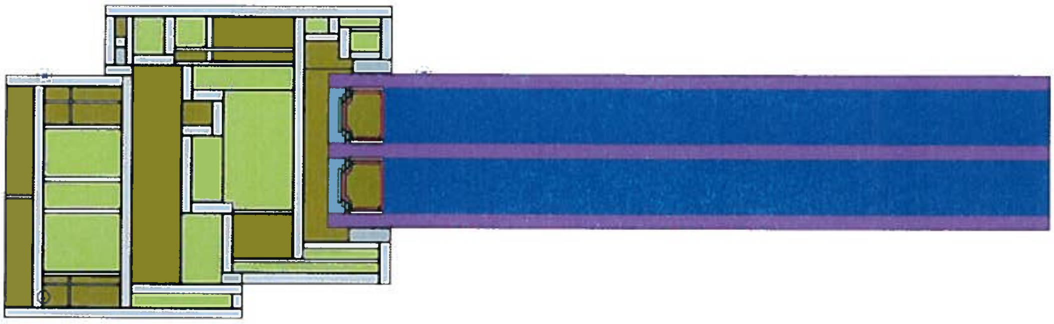


Figure 8 PVC frame with polyurethane foam insulations

Type 4. Next construction represents a simple wooden frame with some air cavities. It is shown that this material is used in compact shapes due to the characteristics of wood. Again the EPDM has been used for joints between different parts of the frame.

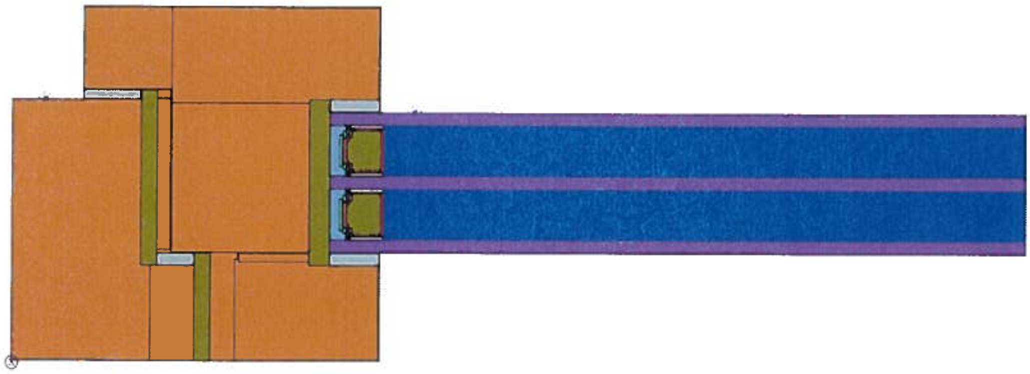


Figure 9 Wood frame with air gaps

Type 5. In Figure 10 it is shown an aluminium frame again, with polyurethane foam, but the difference with the first type is the spacer which is changed from a Swisspacer-V to a Super Spacer. This has been calculated to corroborate the importance of the spacer in the calculation of the U-value.

Figure 10 Aluminium frame with polyurethane foam and Superspacer

Type 6. In Figure 11 a PVC frame without any insulation component is represented, just with air cavities and some steel components to help the structure keep the shape.

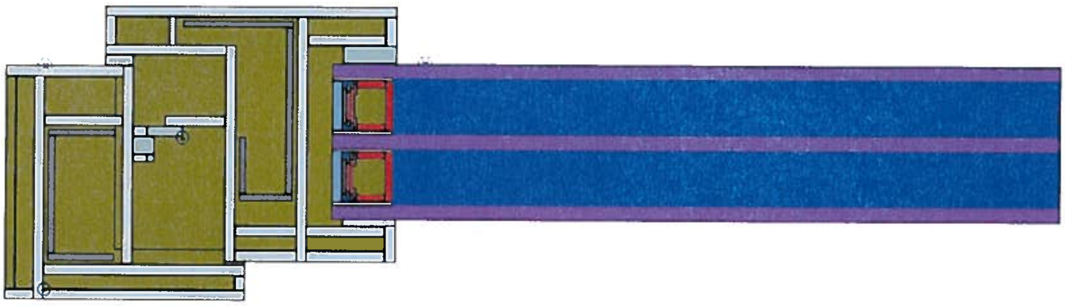


Figure 11 PVC without polyurethane foam insulation

Type 7. Figure 12 shows a wood frame, but made of cypress wood that has a lower thermal conductivity than the soft wood previously used.

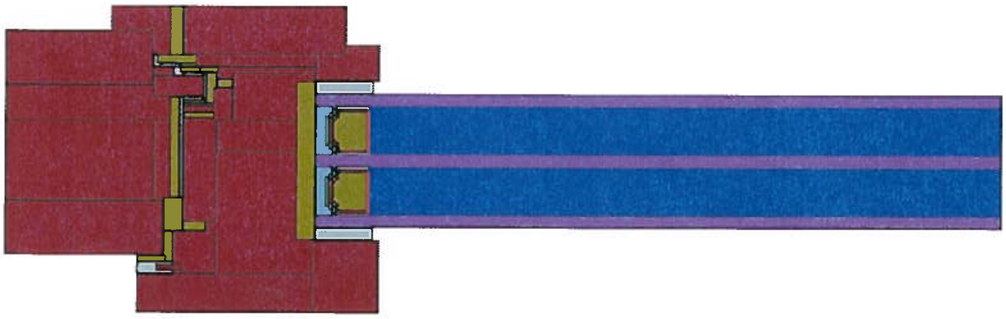


Figure 12 Cypress wood frame

Type 8. The window represented in Figure 13 has the same frame than the one made of PVC and polyurethane foam insulations (type 3). We used this one because it was the one that showed the lowest U-value. The change has been made in the glazing part, changing to a quadruple pane with krypton filling. This has been tried thinking on the good thermal quality of the glazing part, as krypton has a very low conductivity. This fact could lead to a considerable decrease of the U-value.

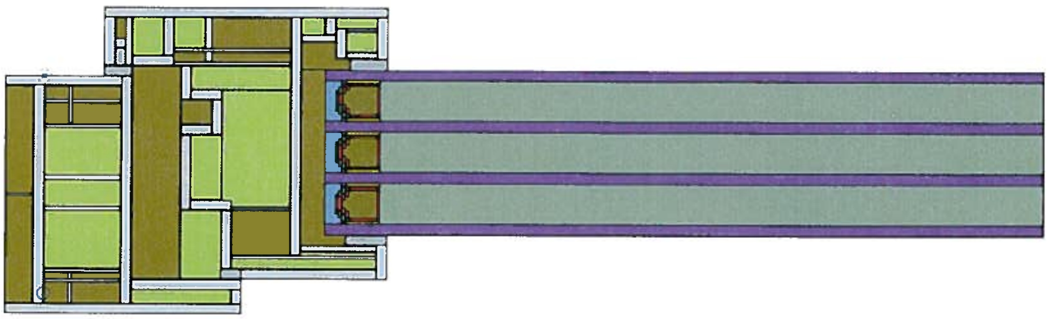


Figure 13 PVC and polyurethane foam frame with krypton filling in the air gaps of glazing

Type 9. The last window, shown in Figure 14, has been made of cypress wood. The design of the frame has been changed from type 4, in order to improve the values of the thermal transmittance.

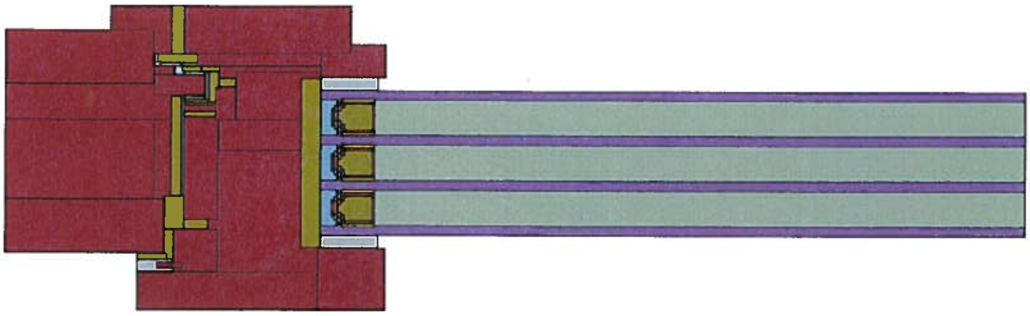


Figure 14 Cypress wood frame with krypton filling in the air gaps of glazing

Finally, Figure 15 shows the Swisspacer-V used in almost all the calculations because it has demonstrated to be the most valuable one. The information about the design and materials used for this spacer has been obtained from its manufacturer, Saint-Gobain Glass Solutions (SGG). It is made by two butyl rubber panels (yellow), one cover of styrene acrylonitrile (SAN) with a 35% of fiber glass (red) involving the silica gel (desiccant) (brown), a thin layer of stainless steel foil (green) and everything attached to the glass by a polysulfide (grey).

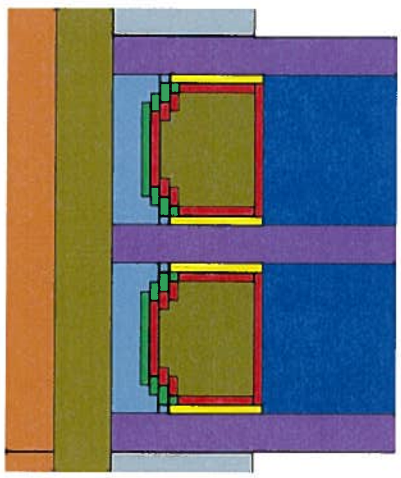


Figure 15 Swisspacer-V

Once the models are designed and all parts are put together we start the simulations and obtain the results of the heat flows through the structure of the window. The program gives information about the changes in temperature and the changes in heat flow with a color scale. In Figure 16 it is clearly appreciable the results by the colour changes, but numerical information about the values in the boundaries could also be exported.

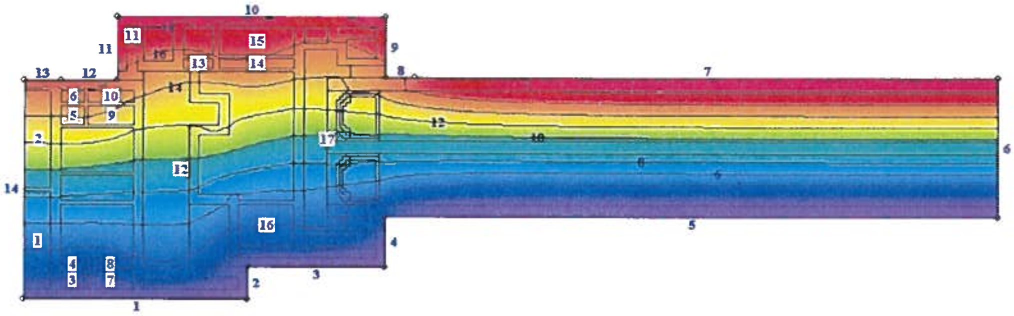


Figure 16 Post-processor for calculation of U-value, changes in temperature

The glass used in the first seven simulations shown is a triple pane glass with 4mm glass thickness and 16mm width space between the glass pieces. The glass material is soda-lime glass and the gas contained in the spaces is a mixture formed by 90% of argon and 10% air. This has been the glazing selected for the calculations as the Table 4 shows, because it has fulfilled the requirements better than the other ones tested.

When the number of panes and the low-emissivity coats are increased, by applying different shading materials, to raise the thermal insulation property of a window, the optical properties get affected. The emissivity of the low-emissivity coatings used is 0.037, 4% Ag. There exists a trade off between these two properties. The glass with four panes has the best insulation but it can decrease daylight admittance. Another reason, why the 4 mm triple glass with two low-emissivity coats was chosen, was the price. The one super insulated is filled with krypton instead of argon which involved an increase in the glass costs. While the price of 99.995% pure krypton gas costs 165.50€/dm^3 in small quantities (1dm^3) and about 4.51€/dm^3 in large quantities (300 dm^3), the price of 99.999% pure argon gas costs 169.90€/dm^3 in small quantities(1dm^3) but about 1.84€/dm^3 in large quantities (300 dm^3) (Generalic 2003). This means that the krypton is almost 2.5 times more expensive than argon. At the same time it could be heavier due to the four panes and the triple air-gap, what it is not interesting from a structural point of view. The calculation of the U-value of glass has been calculated following the standard EN 673.

Table 4 U-values ($W/m^2 \cdot K$) for different kind of glass (Ug) according to EN 673

Number of panes	Thickness of glass (mm)	Air gap (mm)	Emissivity	Gas	U-value
3	4	12	No coating (0,9)	100% Air	1,895
3	4	12	No coating (0,837)	10% Air+ 90% Ar	1,760
3	4	14	No coating (0,837)	10% Air+ 90% Ar	1,673
3	4	12	2 Low-ε (0,037)	10% Air+ 90% Ar	0,721
3	4	14	2 Low- ε (0,037)	10% Air+ 90% Ar	0,578
4	3	12	2 Low- ε (0,037)	10% Air+ 90% Kr	0,279

3.4 U-value comparison for different types of window frames

The heat transmittance values for the different types of windows presented in Section 3.3 are shown in Table 5. The value shown is for the whole window (frame, spacer and glass), but the glazing area has not been presented because it is the same for all cases.

Table 5 Results of U-values for the types of windows

Model	U-value-just frame ($W/m^2 \cdot K$)	U-value for glass ($W/m^2 \cdot K$)	ψ(W/m·K)	U-value-whole window ($W/m^2 \cdot K$)
1) Aluminium+polyurethane	2,454	0,578	0,041	1,246
2) Aluminium	3,024	0,578	0,034	1,438
3) PVC+polyurethane	0,991	0,578	0,033	0,784
4) Wood	1,04	0,578	0,037	0,81
5) Aluminium+superspacer	2,461	0,578	0,102	1,399
6) PVC	2,099	0,578	0,04	1,136
7) Cypress Wood	1,024	0,578	0,035	0,8
8) PVC+krypton	1,022	0,279	0,029	0,575
9) Cypress wood+krypton	1,039	0,279	0,029	0,579

The main conclusion that can be assumed from these results written down in the table is the good insulation capacity of the PVC when it works as a frame. This is because the construction capacities of this material permit the design of small cavities and multiple shapes. Therefore several modifications can be done on these kinds of frames to look for the most convenient one to reach the desired goal.

In order to prove the benefits of the insulations located in forms of polyurethane foam another PVC frame was simulated. This time, air cavities have only been used between the polyvinyl chloride pieces of the structure. The difference is quite substantial expressed in a change of 0.352(m^2·K) in the U-value between both designs. The results show that a good distribution of the correct insulation material significantly improves the thermal characteristics of the window.

For a clearer interpretation of the values obtained the graph in Figure 17 is shown.

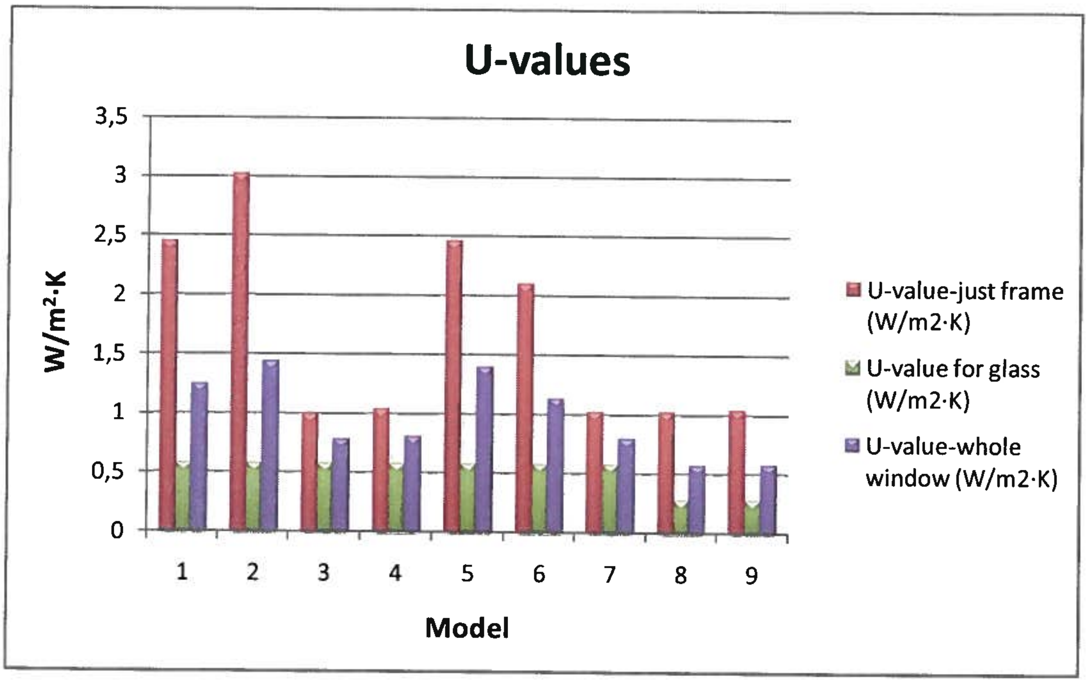


Figure 17 Graphic representation of the U-values of the models

In further calculations, wood has been used for developing the window. The insulating performance of this material is clearly significant, but its manufacturing properties do not allow the same flexibility as PVC because this material has rougher structures. For this reason, the capacity of modifying wooden designs has always presented more difficulties and a smaller action angle. At the same time the combination with different insulation materials has never reported enough improvements in terms of heat transfer. So, it has only been possible to develop these frames with air cavities and also with EPDM for construction issues. In the calculations, two patterns have been shown in order to compare two different possibilities for this frame material.

The other material tested in frame structures was aluminium. The results obtained reveal that this is not a good option in terms of thermal transmittance. It is clearly demonstrated that the U-values for these cases are much higher than the values of other materials. The chances of modifications of these frames are not as high as the PVC ones and the conductivity is also higher for aluminium. For these frames diverse modifications in materials utilization have been tested. As it is possible to see in the figures from the previous section the changes have been done in the insulation materials used for frames cavities

The use of polyurethane foam as an insulator helps improving the U-value of the frame and therefore that for the whole window. This material has also been used for PVC frames and has provided good results. So, we have considered the polyurethane foam as the best insulation technique for frames. Another material used for all frames tested has been the EPDM. Its function is to act as a connecting element between different parts of the frame and between the frame and the glass.

The most critical part of the window has been the spacer, so it has led to the most arduous search with the purpose of finding the most appropriate one to achieve the desired objectives. Different information about spacers of different manufacturers has been used to create several designs. After that, they have been simulated to find out the best option available for decreasing the U-value. The result is the utilization of one called Swisspacer-V and manufactured by Saint-Gobain Glass. It is shown in the table 5 from this section the effects of a different spacer. Edgetech has developed a product called Super Spacer made of silicone foam and a thin layer of alumium. This spacer has been tested in an aluminium frame and the result for the U-value has been worse than most of the other options. This fact reinforces the theory about benefits of using the Swisspacer-V to reach the target.

There are more companies engaged in manufacturing of spacers, e.g. Helima, Ensinger and Roll Tech. All of them offer different shapes and materials utilization for the construction of their products and give specifications on their technical catalogues about them. They have been simulated in HEAT2 to test their capacities, but none of them have satisfied the values as good as the Swisspacer-V.

To show the differences between using one or another kind of spacer, the same model but with different spacers were tested. The window model used was the aluminium and polyurethane foam insulations frame with triple pane glass and argon filling in the spaces between panes. The best spacer, Swisspacer-V, was compared to the Superspacer.

Table 6 Relation between both spacers

Spacer	**U-value ($W/m^2 \cdot K$)**	**Ψ-value ($W/m \cdot K$)**
Swisspacer-V	1,246	0,041
Superspacer	1,399	0,102
Change (%)	12,28%	148,78%

It can be seen that the best U-value is obtained for the Swisspacer-V, with a difference of more than 12%. However, the best improvement has been observed for the Ψ-value, which has a significant improvement of almost 150%. This is due to the location of the spacer, right on the frame and glass bonding. Therefore the Swisspacer-V has been proved to show the best conditions to be considered more useful than other spacers.

The last part treated in this section is the glass of the window. It has been chosen a triple pane of soda-lime glass that has a conductivity of 1 W/(m·K). The spaces between panes are filled with a mixture of 10% air and 90% argon. This combination of gases gives good results for avoiding heat loss. The thicknesses of the spaces are 16 mm and for the glass panes are 4 mm each. The conductivity for the outer space is 0.0198 W/(m·K) and for the inner space is 0.02 W/(m·K). At the same time two low-emissivity coats of 0.037 are applied on the outer and inner glass. The U-value obtained for the structure of the glass is 0.578 W/(m²·K). For different glass tested, this option has been decided to be the most reasonable one.

Depending on the U-value obtained for the window studied, there are different levels stablished in Sweden. The purpose of this method is just to categorize the windows according to their U-value. Starting category A with the lowest U-value and finishing in category G with the highest.

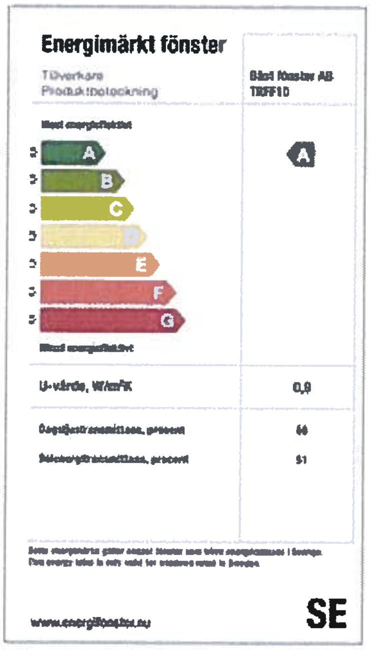


Figure 18 Categories of U-values in Sweden

The U-values for the different labels are:

A: U-values of 0.9 W/(m²·K) or lower.

B: For U-value of 1 W/(m²·K).

C: For U-value of 1.1 W/(m²·K).

D: For U-value of 1.2 W/(m²·K).

E: For U-value of 1.3 W/(m²·K).

F: For U-value of 1.4 W/(m²·K).

G: For U-values of 1.5 W/(m²·K) or higher.

Window Energy Rating Labels determine how a window will fulfill different functions such as resist condensation or insulation of outdoor temperature changes. By comparing different labels, builders and consumers can choose between different options regarding the energy performance of each choice. The basic label lists the manufacturer, describes the product, includes the essential energy performance data and provides a source for additional information.

3.5 Improvements for reaching lower U-values

In this section some improvements studied in order to reduce the U-value of the window are presented. First an improvement for the frame part is shown and afterwards changes on the glazing part are exhibited.

3.5.1 Frame part

In order to reduce the U-value of the wood frame, it has been replaced by a fictitious material that has a lower thermal conductivity. However, the design and dimensions have not been changed. For this material the value of the thermal conductivity has been chosen randomly, in order to see the difference of the value with the change of the thermal conductivity. In Table 7 these changes are clearly represented.

Table 7 Changes in U-values related to changes in thermal conductivity of the frame

Model		**λ (W/m·K)**	**U-value (W/m²·K)**	**Ψ-value (W/m·K)**
4	Wood	0,11	0,81	0,037
	Ficticious material	0,07	0,732	0,035
Change (%)		36%	9,63%	5,41%

It is possible to see that the change in the U-value is significant. With a 36% decrease in the thermal conductivity of the material the U-value has been reduced almost 10%. This shows that changes in this direction help to reach the goal of obtaining the lowest U-values.

To conclude with this investigation it should be said that further work should focus on improving the materials used for the frames, because they have worse values than the glazing part. These materials should have a lower thermal conductivity but they should fulfill the structural properties of the materials currently used for this purpose. It has been demonstrated that a decrease in thermal conductivity of the frame represents an important reduce in the thermal transmittance of the whole window.

Another improvement, in order to reduce the U-value of the structure, consists of increasing the frame part over the glazing. What it has been developed with this investigation is to decrease the effects of the thermal bridge between frame and glazing. It has been tested in type 4, with a wooden frame. The results showed that the U-value has been reduced from 0.81 $W/m^2 \cdot K$ to 0.674 $W/m^2 \cdot K$ (16.8%), while the thermal bridge has been reduced from 0.037 W/m·K to 0.026 W/m·K (29.7%). The thermal transmittance of the window has been improved but at the same time visibility is lost.

3.5.2 Glazing part

To improve the U-value of the window the glass was replaced by a polycarbonate. It has been tested for a window made of a PVC and polyurethane foam insulations frame. This frame has been chosen because it showed the best U-values among all the frames checked.

Polycarbonates have lower thermal conductivities than glass, for this reason it was thought that the U-value of the glazing part would decrease and therefore the total U-value of the window.

Table 8 Comparison between glass and polycarbonate

Material	**λ (W/m·K)**	**U_g ($W/m^2 \cdot K$)**	**U-values (W/m2·K)**	**Ψ-value (W/m·K)**
Glass	1	0,579	0,784	0,033
Polycarbonate	0,2	0,566	0,744	0,02
Change (%)		2,25%	5,10%	39,39%

As it is shown in the Table 8, the U-values of both parts have decreased with the application of the polycarbonate. However, this decreased is not very significant compared to the difference between the thermal conductivities of both materials. From this result it is concluded that the most relevant part of the glazing is not the glass but the spaces between the panes.

It is observed that the biggest improvement of the change from glass to polycarbonate is the thermal bridge between frame and glazing. This is due to the low thermal conductivity of the new material used for the glazing, what decreases the heat transmittance between both parts.

When the glazing part of the window wants to be improved, there are two different ways. Focus the improvements on the panes or on the spaces. Previously it has been shown some changes made in the panes of the glass, replacing the glass for polycarbonates.

Now, the improvements have been tried in the spaces between the panes. The gases used before for filling these spaces where the best possible options, argon and krypton. To avoid the effects of convection it is needed to fill the space with a solid or with vacuum instead of using gas.

The solid chosen for this purpose has been an aerogel blanket, which is a known solid with a very low thermal conductivity. The results for the calculations of the U-values of the glass with these fillings are shown in the next table. The values can be compared between the combination of argon and air, vacuum and air, and aerogel.

Table 9 U-values of the glazing part depending on its filling

Number of panes	**U_{glass} (W/m^2·K)**	**U_{glass} (W/m^2·K)**	**U_{glass} (W/m^2·K)**
	10%Air + 90%Argon	10%Air+ 90% VACUUM	Aerogel
2	1,31	0,40	0,98
3	0,72	0,19	0,64

It can be observed in the table the significant difference between using gas or not. It has been tested for glass of 2 and 3 panes and the thickness of the spacers between panes is 12 mm. The improvement of using vacuum, which has an extremely low thermal conductivity, for the space is huge as it is shown in Table 9. The reduction of the U_{glass} for vacuum spacer, in comparison with argon filling, is 69.5% for double pane and 73.6% for triple pane. The change for using aerogel, that has a thermal conductivity of 0.014 W/m·K, is not as big as the one for vacuum, but it still represents an outstanding improvement.

But the use of these materials has drawbacks as well. The implementation of vacuum in the space is not an easy task. The space between panes should be enough thin so that the pressure on the glass is not too big. Even so it is hard to make a construction where the vacuum remains in the space. In windows with vacuum, there are spacers that separate the panes.

The problem of the aerogel is that it is not completely transparent, so some effects of light flow through it are missing with its use. Further work on this material should focus on make it as much transparent as possible.

4 Solar effect optimization in windows

The main purpose of a window is to allow the sunlight inside the building without changing the colour of the light. Another basic reason for using this structural component is to create a visual contact between the inside and the outside.

Depending on the geographical region where the building is located and the climate found there, it may be positive to capture the heat from the sun, in cold weather, or avoid it, in warm one. It is also wanted to avoid the UV part of the radiation since it fades the colours of textiles and wallpapers. As it is recommended in the Swedish code, the window glass area should be at least 10% of the floor area. The glass area must be increased if other buildings block the daylight more than 20° of the view angle (BFS 2006:12).

The use of windows has several benefits such as connection to the world outside, access to the environment and contact to sensory change. On the other hand, privacy is another matter to take into account. Two concepts must be differentiated: visual access, which is directly related to the ability of seeing, and visual exposure, which is related to the possibility of being seen. A good combination of both concepts is desirable.

To counteract the high emissivity of glass for long-wave radiation, low-emissivity coatings are applied. These coatings return heat back to its source. When the outdoor temperature is high they do not let the heat go inside and when is low they do not let the heat leave the building. Moreover, low-emissivity coatings can block UV rays and long-wave infrared heat without preventing visible light from passing (SeriousWindows 2011).

4.1 Improvements for low energy windows

In this section some proposals for improving the efficiency of the window with respect to solar radiation is suggested. It is divided in two parts, developments on the glazing and installation of roller blinds.

4.1.1 Smart glass

New materials for glazing of windows are being researched all the time. So, in December 2010, a new concept of glass for windows was discovered by the National Renewable Energy Laboratory of the U.S. Department of Energy. It is a system that obscures the glass when the heat affects them, this way the solar radiation effects are avoided. When the window gets colder the glass becomes transparent, allowing the passage of light and therefore heat.

This device just offers advantages because all this is possible without using any electricity consumption. To achieve this, an organic plastic polymer which is sensible to temperature changes is placed between the panes of the glazing. It works as a filter and it is also able to adjust it for different temperatures wished in the inside atmosphere.

The colour of the glazing does not change; it just turns transparent or opaque. It could be consider as a natural heating system. The energy saving would vary between 30% and 40%.

These features make this device very capable for reaching good insulation on windows (Dalberte 2010).

It satisfies two conditions, avoiding bad effects from solar radiation and having no consumption from the energy supply. For this reasons it is very interesting to take into account this kind of glazing when good rates of insulations want to be reached.

Another smart glass has been developed at ChromoGenics AB, a world leading group in electrochromic materials. It is located in Uppsala, Sweden, and it is a continuation of with the work developed during years at the Ångström Laboratory.

The innovation done in this field by this group consists of creating a flexible and light-weight electrochromic foil. This layer is capable of changing its darkness degree by applying an electrical voltage of a few volts. For this issue a multilayer-structure comprising different materials between two plastic films is used, as it is shown in the figure below.

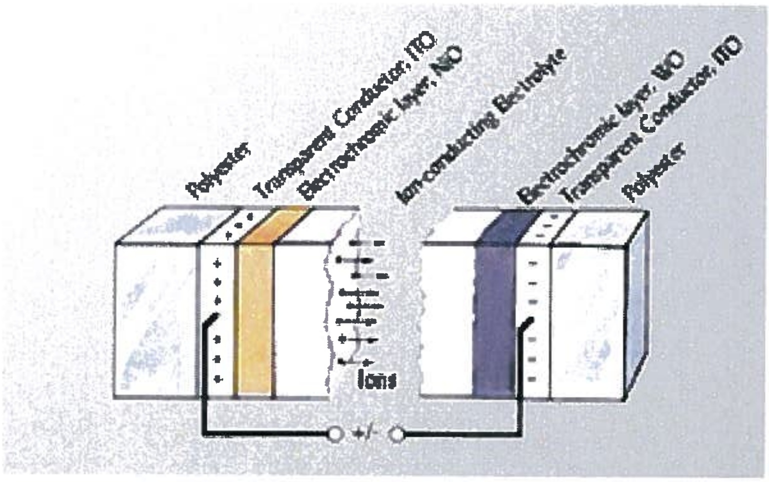


Figure 19 Cross section

When the voltage sends ions from a layer of nickel oxide to a layer of tungsten oxide, these layers become darker. If the polarity is reversed the direction of the ions flow changes and makes the layers brighten. It is possible to regulate the level of darkness wished by an electronic control unit. When this level is reached the properties are hold until the next change is executed.

The foil only uses electricity when its degree of darkness is altered which makes it very energy efficient comparing it with other techniques. The range of applications of this product is very large which makes it better than its competitors. One example of properties that could be change is the colour and shape of the product, what leads to a wide field of application (ChromoGenics 2009).

The use of this product could be very interesting for the aim of our work. The main idea is to save energy from heating and cooling systems by using a little bit for the correct shading of the glazing part of the window.

Another device that works towards energy efficient in window glass has been developed by the Massachusetts Institute of Technology. It consists of the installation of organic molecules to take advantage of the energy from the sun's infrared light. At the same time its function is to allow the flow of the natural light through the window to provide the inside environment of the building with this light. The photovoltaic cell formed by the organic molecules makes the light transformable in electricity or heat in the inside.

This sun collector was made by adding two or more dyes and impregnating a glass or plastic panel. The light is absorbed in a wavelength range to be emitted afterwards in a different wavelength and driven then through the solar cells.

The installation of this device would lead to energy savings because it would not be necessary to provide solar panels to the buildings. With this system the windows work as solar collectors so the area of action is bigger since they do not need to be just on the roof.

However, until now the work has not been completed since the efficiency achieved is 1,7%. Further efforts will try to reach the expected target of 12% to equalize the current solar panels that nowadays can be found in the market. The fact of having this device on the windows would allow the system to take advantage of the sun energy during the early and late hours of the day, when the panels over the roof would not receive good sun radiation.

One of the advantages of the work developed is that the manufacturing method enables the installation of this product in already made windows. For this reason, the integration in the building market will be easier and a successful consumer approval could be predicted (Peña 2011).

4.1.2 Roller blinds

A blind is a mechanical device that is placed on the outside or inside of a window or balcony in order to protect the room from heat or light. The blinds can be made of different materials well-known for their resistance to deterioration and lightness, e.g. PVC and aluminium. Wood is also common in venetian blinds due to good insulation properties of this material.

Different kind of blinds:

- Rolling
- Venetian
- Folding horizontal and vertical
- Vertical slats

Blinds provide thermal and sound insulation, avoid the entry of wind, dust or light when it is necessary. These characteristics lead to energy savings and comfort for our houses.

For this analysis, rolling blinds were selected. The blind consists of a roller system, which is attached to the top of the window frame. The position of the blind would be inside of the room, over the frame, as shown on Figure 20 (the Figure 21 presents a detail of the roller blind which is in the interior of the box).

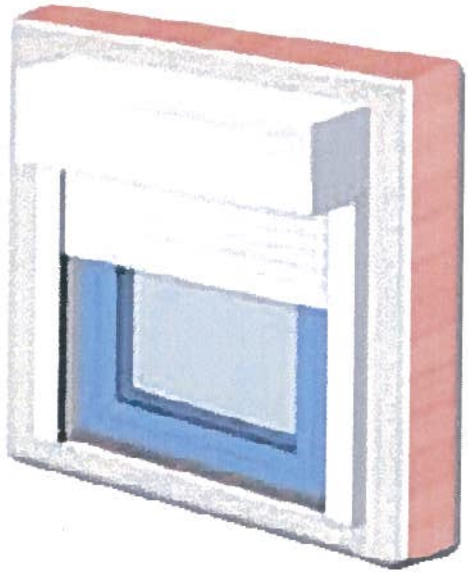


Figure 20 Window with a roller blind inside of a room

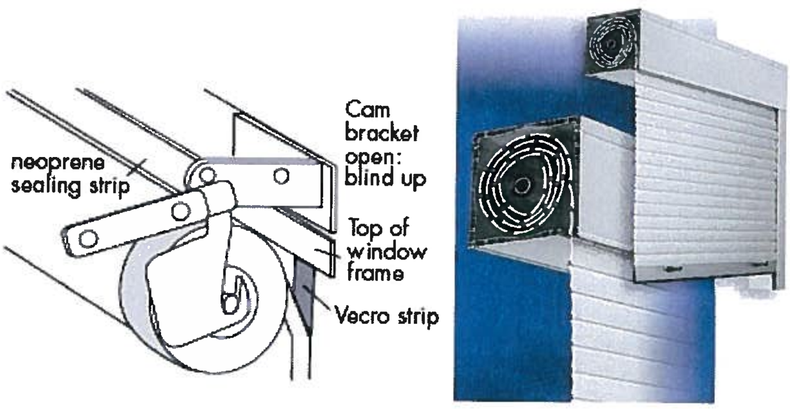


Figure 21 Details of the roller blind (Conservatory Comfort 2009)

It has been decided to settle the blinds indoors as a consequence of the Scandinavian climate. They should be easy to operate, lightweight and provide easy ventilation. The maximum width recommended is 1.5 meters (Conservatory Comfort 2009).

Blinds are of high relevance when talking about the thermal convective properties of a window. Although the models for simulating such effects are still not fully comprehensive, actual approximations have shown a strong relationship between the distance of the blind to the glass and the position of it. According to EN ISO 10077-1:2006 (E) the equation 14 represents the new U-value when applying a blind.

$$U_{WS} = \frac{1}{\frac{1}{U_W}+\Delta R} \quad \left(\frac{\mathrm{W}}{\mathrm{m^2 \cdot K}}\right) \tag{14}$$

U_{WS} is the thermal transmittance of the window with closed shutters $\left(\frac{\mathrm{W}}{\mathrm{m^2 \cdot K}}\right)$

U_W is the thermal transmittance of the window $\left(\frac{\mathrm{W}}{\mathrm{m^2 \cdot K}}\right)$

ΔR is the additional thermal resistance due to the air layer enclosed between the shutter and the window and the closed shutter itself $\left(\frac{\mathrm{m^2 \cdot K}}{\mathrm{W}}\right)$ (see Figure 22)

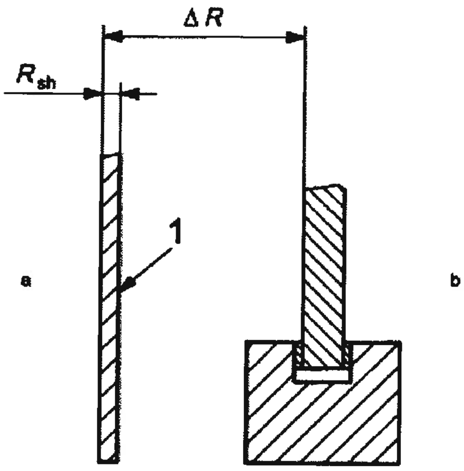


Figure 22 Window with internal shutter (EN ISO 10077-1:2006 (E))

Key:

[a] represents indoors

[b] represents outdoors

1 represents the shutter

For example, if the blind is too far away from the glass, the convective exchange between the two approaches to zero and the convective heat transfer occurs individually on each element. On the other side, if the blind is so close to the window that they actually touch each other, the individual convective phenomena can be disregarded. For middle points between extremes, the heat transfer coefficients can be approximated by an exponential decay. To conclude, the presence of blinds greatly modifies the thermal convective exchange between indoors and outdoors. This effect can be calculated but it varies considerably in the dimensions and positioning of the blinds; the indoors of the blinds being the most important part for solar absorption and to convert all this energy into convective cooling load (Lomanowski 2008).

In order to achieve the best insulation possible, wood frame around the window in the outside of the building wall should be placed. Figure 22 shows the window with the wood frame and the blind box. The length should be between 30 or 50 cm and should have a small slot to avoid moisture in the corners of the window frame.

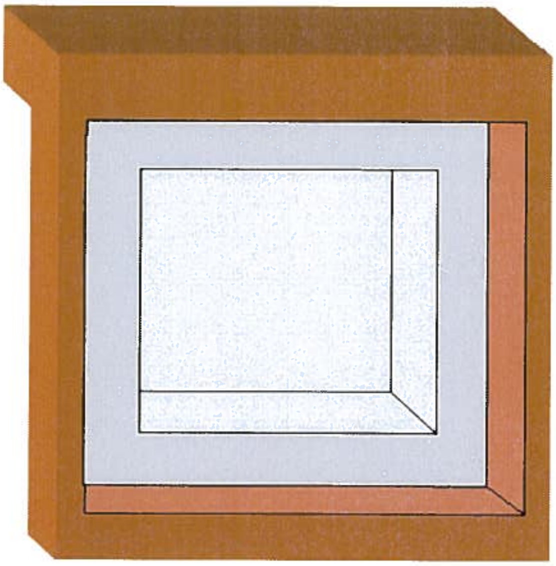


Figure 23 Window with wood frame in the outer of the wall and the box for the blind

4.2 Improvements reached by applying a blind

In order to improve the value of the heat transmittance through the window, a blind was applied to the structure. It was located in the inside of the room, due to the Scandinavian climate. The extremely cold weather could freeze the blind structure. This would not let the blind go up to the box where it remains when it is open. For this reason, installing the blind in the inside of the window was a better option to solve this problem.

The next step was to see if applying a blind in the inside of the building, condensation would take place on the inner pane of the glazing. To check this phenomenon it was firstly consider the relative humidity of three different areas of Sweden and the results are shown in the figure below.

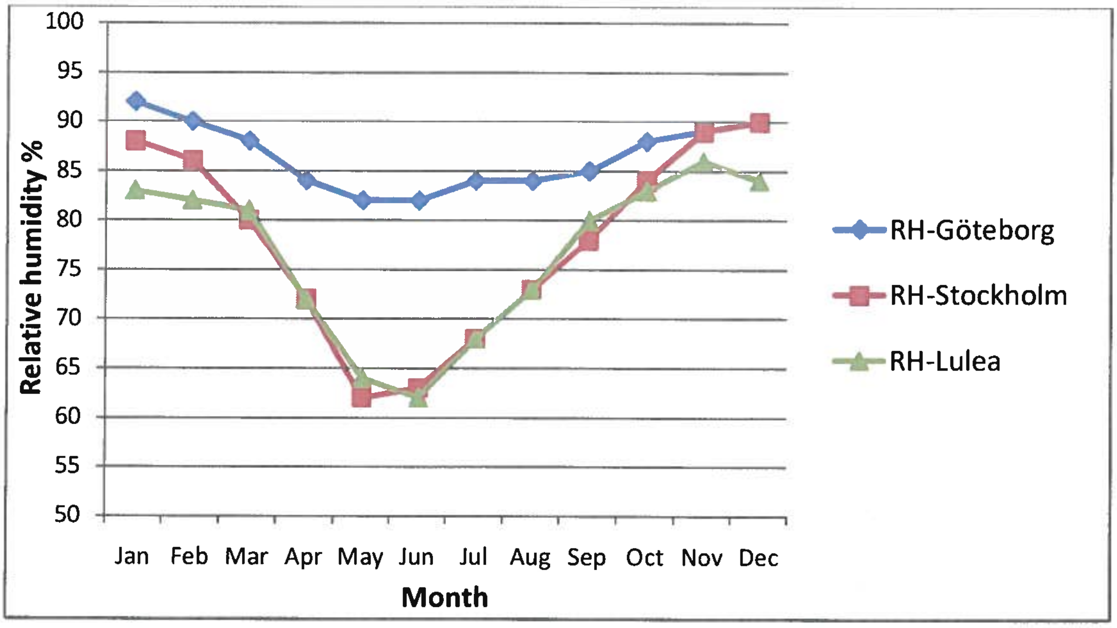


Figure 24 Outdoor relative humidity for Sweden

Taking into account these values the vapor content of the inside in the inner pane of the window has been calculated for a PVC window with U-value 0.784 $W/m^2 \cdot K$. According to a recent study made in over 1800 Swedish modern buildings, the increased of the vapour content, from outdoor to indoor, has been considered 1.2 g/m^3. For this condition no condensation was found in the inner pane of the window for any of the models calculated.

However, when the increase of the vapour content is considered 4 g/m^3, condensation is formed for an outside condition of -27.1 °C in Luleå, and a U-value of the window of 1.4 $W/m^2 \cdot K$. This increase was considered in order to satisfy bigger formations of vapour content due to different activities in the dwelling. The results show that the application of a blind is always possible if the U-value of the window is relatively low.

For this case the decrease in the U-value of the model of window 3, from Chapter 3, is from 0.784 $W/m^2 \cdot K$ to 0.636 $W/m^2 \cdot K$ that is almost a reduction of 19%, when a PVC blind with polyurethane foam insulation is used. This decrease makes the application of this device very efficient.

The blind would be installed in the wall frame, where the window is installed as well. It would mainly use when there is no daylight outside, because it would not allow this light to come in during the day but it could be also used to avoid effects of solar radiation.

4.3 Effect of solar radiation and lighting in windows

4.3.1 Solar radiation

Radiation can be explained as a process in which photons or electromagnetic waves travel through a medium. There are two types of radiation, non-ionizing and ionizing.

The effects of solar radiation on windows vary considerably depending on its wavelength. Such radiation can be divided into four main categories: Ultra Violet (UV) radiation, visible radiation, near IR radiation and IR radiation. Windows must consider each type of radiation as they affect the building temperature and energy loss changes considerably.

The first type, UV radiation, has a minimum role in the energy balance of the building; however it can be injurious for the people living in it. UV radiation has a wavelength smaller than 380 nm. The transmittance of UV radiation through glass is very small; however a part of it crosses and is the responsible for human bodies getting tanned and paintings bleaching. It is possible to install special glasses that stop UV radiation; however bleaching will still be a problem as the red spectrum of normal light also contributes to this effect.

The second kind of radiation, with a wavelength between 380 nm to 780 nm is visible radiation. This is the radiation human beings and other animals interpret as light and we use to illuminate our buildings and living spaces. Approximately half of the energy the sun emits to the earth is in light making this kind of radiation spectrum the most important one. Windows have very high transmittance of this radiation as light passes through windows glass with little losses. However, not all light energy is transmitted through the window; about 10% bounces from it is absorbed as heat. This effect is increased with the addition of several panes.

The second most important interval of the sun's radiation emission is the one with a wavelength between 780 nm to 2500 nm. This interval is called near-IR radiation and is the part of solar radiation that reaches the earth while not being visible. It represents about 40% of the energy that the sun transmits to the earth.

The last type of radiation is IR radiation which has a wavelength over 2500 nm. Most of the surfaces in a building at room temperature emit this kind of radiations. Although windows are opaque for this kind of radiation, the energy is absorbed and then radiated in all directions. In the case of the windows glass, the energy is absorbed by the glass and then radiated in all directions, making considerable energy losses when radiated outwards the building. Through this mechanism, a large part of the heat is lost from the inside of a building.

The electromagnetic spectrum of the non-ionizing solar and the ultraviolet radiation is shown in Figure 25 while Figure 26 shows the wavelength of solar radiation.

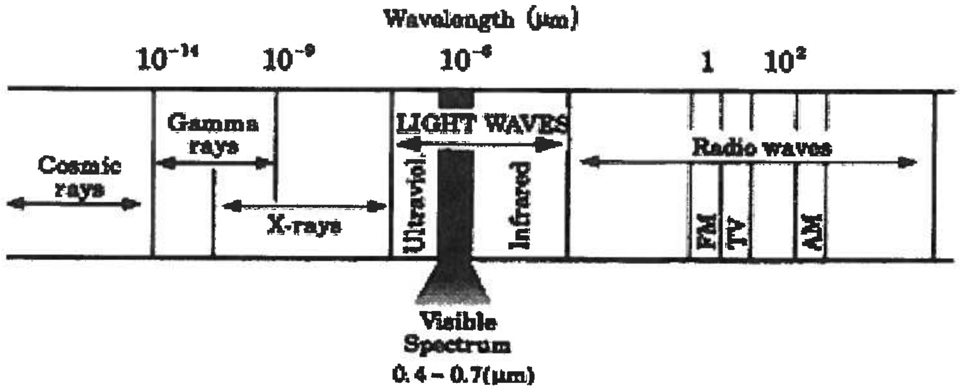


Figure 25 Spectrum of electromagnetic radiation (ecological psychology 2001)

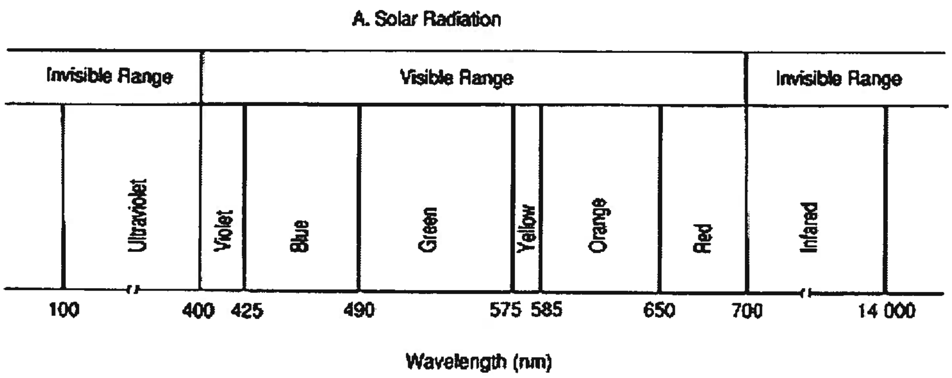


Figure 26 Spectra of non-ionizing solar radiation showing main radiation bands, their nomenclature, and approximate wavelength limits. (Compiled from WHO 1979; Parmeggiani 1983; Harvey et al. 1984) (Acra, Jurdi, Mu'allem, Karahagopian & Raffoul 1990)

The calculations of the solar radiation through different kind of glass were performed with the program WINDOW 6.

4.3.2 Lighting

Windows should be designed so that a satisfactory thermal climate can be achieved. Some reasons why windows are so important for construction issues are based on letting the light come into the building and providing view out and sometimes view in too. Daylight should be enough to satisfy the human needs. The main factors that define the daylight in a room are the size of the window, the kind of glass, the orientation and location of the window.

The proper light conditions are reached when no disturbing glare or reflections take place on the inside and at the same time correct lightness (luminance) and intensity of light are achieved (BFS 2006:12).

Solar radiation is constantly varying and has different distribution in the entire world since it depends on variables such as solar latitude and altitude (vary according to the season of the year) or cloud amount and pollution levels. In Northern countries like Sweden, completely sunny days are not usual. The daylight in Sweden is performed for Göteborg with the software METEONORM.

General concepts:

- **Daylight**

Daylight includes the direct sunlight, diffuse sky radiation and the reflection of these two coming from the Earth and terrestrial objects. The daylight factor (DF) is the ratio of indoor daylight illuminance to the exterior illuminance for a clear sky of known luminance distribution.

The direct daylight is the one that comes from the outside through the windows and the indirect one enters through other elements of the building, e.g. doors and skylights. The orientation and location of windows will be determined by the amount of direct daylight wished to come into the room. In most of cases it is wanted to receive as much direct daylight as possible and especially in cases when the efficiency of the building needs to be optimized. A good distribution of windows in the building could lead to energy savings in terms of electricity supply for artificial lighting. However, in private homes or residences, windows should not be the only source of light as people spend most of their time in them.

At the same time, windows should allow building occupants to view the progress of the day and perceive changes in the outdoor environment like seasonal weather. The low-emissivity coats decrease the amount of daylight through the panes of glass so they might be used just in cases where climatological conditions are more adverse (cold weather), like Sweden.

- **Direct sunlight**

The term direct sunlight refers to the light that enters the room without having been reflected anywhere before. According to the Swedish code (BBR 2006) at least one room in every dwelling must have access to direct sunlight (BFS 2006:12).

- **Glazing development for solar radiation control**

Solar control glass used to be reached by adding a metal oxide to the glass melt. It would be placed in the outer pane, this way a tinted body would be created. Another case of solar control is based on a soft silver layer placed at the outermost pane and facing inwards. This coating gives the glass a low emissivity property, combining this way solar control with energy efficiency.

One improvement developed is a coated glass with a high ratio between the transmittance of visible radiation (T_{vis}) and total solar energy transmittance ($T_{sol,tot}$). For this reason, this glazing let in most part of the daylight but stopping at the same time solar radiation in the near-infrared region. It is applied in the outer pane facing inwards and it has multiple layers, where the active part is a double silver layer. This confirms the good properties of silver for these purposes.

4.4 Energy consumption in a simple apartment

According to the Swedish building code (BBR 2006:22, Section 9, Energy management), the energy consumption of a building can be defined as "the energy which, in normal use, needs to be supplied to a building (often referred to as "purchased energy") for a period of one year for heating, cooling, hot tap water and operating building installations (pumps, fans, etc), as well as other electricity for the property".

Reducing the energy consumption in buildings by using solar radiation gains is the aim of this process. Studies were performed on two simple concrete walls apartments, one facing north and the other one facing south. The surrounding rooms, roof and floor of the one studied remain at the same temperature, so there is not heat exchange with the adjacent apartments. Therefore, the only wall considered to have heat transfer is the one that has the window as we can see in Figure 27. For calculations and analysis, the same temperature as in the apartments were considered in the apartments around them. The apartment used has an exterior wall area 10m x 2.5m and a floor area 10m x 10m. As said at the beginning of Chapter 4, the window area has to be at least 10% of the floor area, so the choice for this case was 15 m^2 (15% of the floor area). Figure 27 shows a representation of the model.

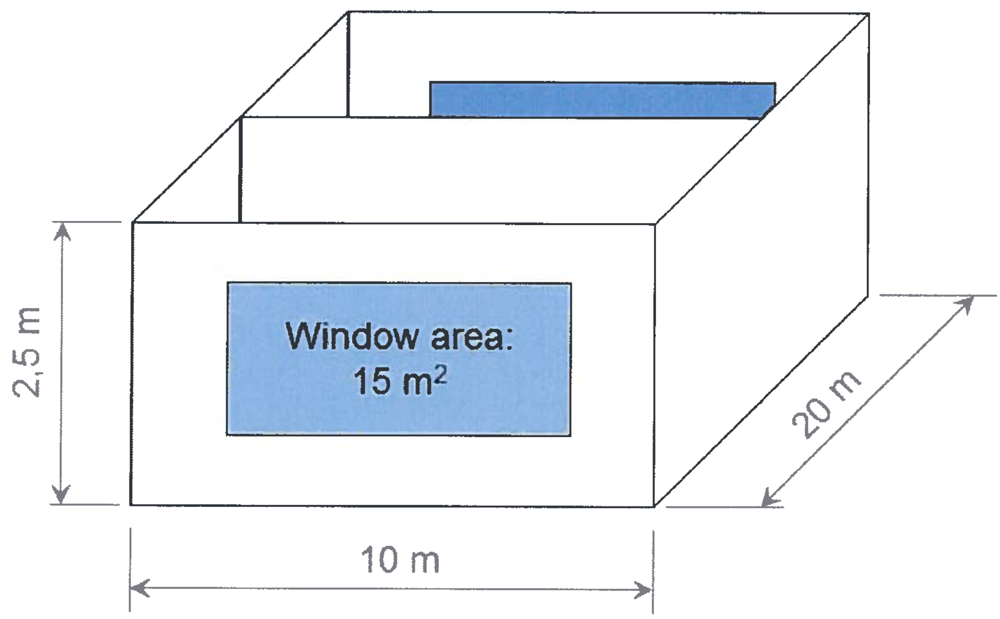


Figure 27 Two different apartments, one facing North and one facing South

Three different cities were selected in order to cover different areas of Sweden: Luleå in the North, Stockholm in the middle and Göteborg in the South. In the following figures, direct and diffuse solar radiation data during a year in these different places are shown, and later used to calculate realize the benefits from solar radiation into a building.

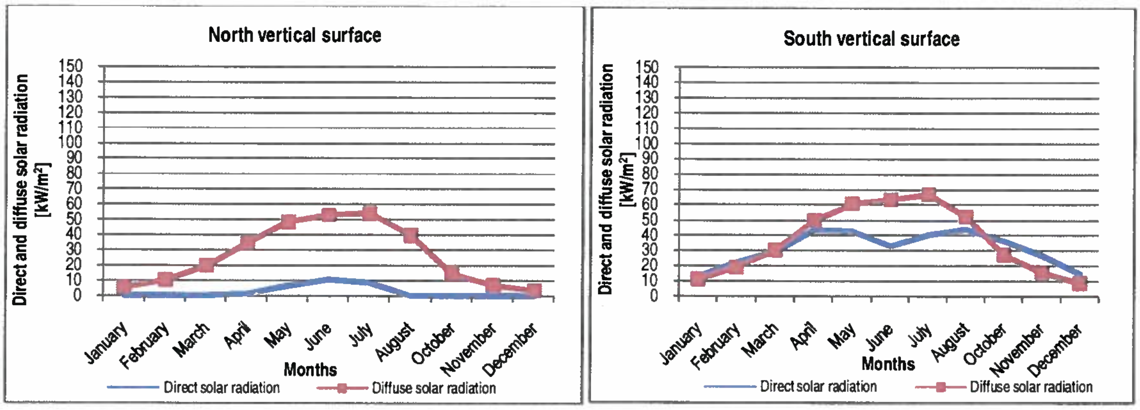


Figure 28 Direct and diffuse solar radiation in Göteborg during a year for north and south facing vertical surfaces.

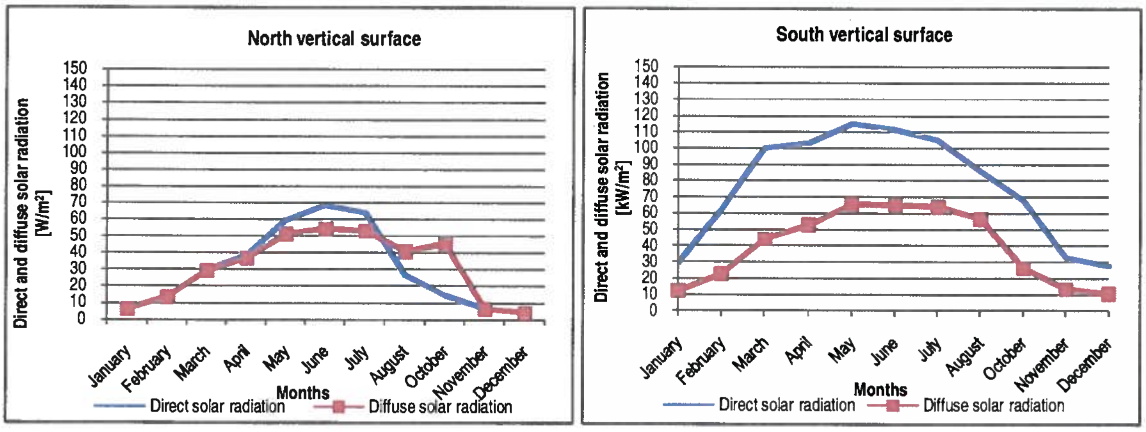


Figure 29 Direct and diffuse solar radiation in Stockholm during a year for four different vertical surfaces.

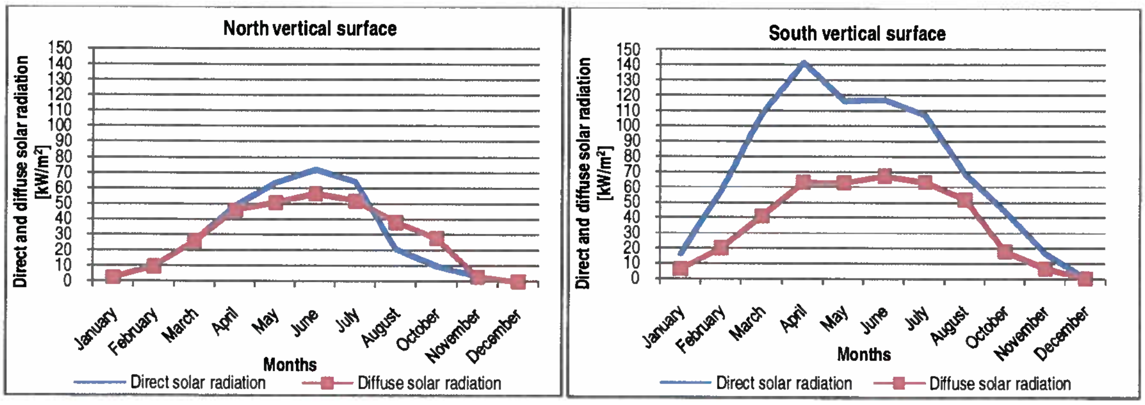


Figure 30 Direct and diffuse solar radiation in Luleå during a year for north and south vertical surfaces.

4.5 Energy balance

The energy balance and the different parameters are described in the following section.

$$Q_{window} + Q_{wall} + Q_{solar\ radiation} + Q_{ventilation} + Q_{internal\ gain} + Q_{supply} = 0 \quad (15)$$

$$Q_{window} = U_{window} \cdot A_{window} \cdot \Delta T \quad (W) \qquad (16)$$

Q_{window} is the heat flow through the window (W)

U_{window} is the U-value of the whole window (W/m²·K)

A_{window} is the area of the window (m²)

ΔT is the temperatures difference between indoor and outdoor air (K)

Two different types of windows were considered, the first type was a PVC window with insulation foam inside the cavity frames and a U-value of 0.784 (W/m²·K). The second type was a PVC window without insulation foam and a U-value equal to 1.136 (W/m²·K).

$$Q_{wall} = U_{wall} \cdot A_{wall} \cdot \Delta T \quad (W) \qquad (17)$$

Q_{wall} is the heat flow through the exterior wall (W)

U_{wall} is the U-value of the wall without window (W/m²·K)

A_{wall} is the area of the wall (m²)

ΔT is the temperatures difference between indoor and outdoor air (K)

The U-value for the concrete wall used was 0.17 (W/m²·K) for both cases, as it can be seen in Section 5.2.3.

$$Q_{solar\ radiation} = I \cdot A_{glass} \cdot g \quad (W) \qquad (18)$$

$Q_{solar\ radiation}$ is the heat flow through the glass due to solar radiation (W)

I is the solar intensity perpendicular to the window for different zones of Sweden for three days of one year, one in summer, another in spring and another in winter (W/ m²)

A_{glass} is the glass area of the window (m²)

g is the solar gain through a window (-) (See Chapter 3, equation 6)

$$Q_{ventilation} = Airflow \cdot \rho_{air} \cdot c_{p,air} \cdot \Delta T = 0{,}5 \cdot V_{room} \cdot \rho_{air} \cdot c_{p,air} \cdot \Delta T \quad (W) \tag{19}$$

$Q_{ventilation}$ is the heat flow due to the ventilation of the room (W)

$Airflow\ of\ the\ room$ is the amount outdoor air into the room (m^3/s)

ρ_{air} is the density of the air (Kg/m^3)

$c_{p,air}$ is the solar gain through the window (kJ/Kg·K)

$Q_{internal\ gain}$ is the heat due to the electricity use in the apartment (W)

Q_{supply} is the heat required to counteract the heat loss (W)

As it has been said in a previous chapter, the solar gain through a window is the product between the solar heat gain coefficient (g-value) and the incident solar irradiance, and can be used to estimate the increase of temperature in an object or space. In this case, the calculations of the g-value were performed with the software WINDOW 6 for the two different kinds of windows. As a low U-value usually has a low g-value and vice versa, in these cases the first type that was a PVC window with insulation and a g-value of 0.32 and the second that was a PVC window without insulation foam and a g-value of 0.65.

In multi-family dwellings, it is reasonable to assume that almost all household electricity is converted into heat gains indoors (approximately 80%). If outdoor lightning or outdoor infrared heaters are used, heat gains from these will obviously not occur inside the building envelope. If dishwashers and washing machines are used in the apartments and the water is heated by electricity, some of the heat will be evacuated through the sewage pipes. Battery-operated appliances (or even toys) might be charged indoors and then used outdoors. Additional heat gains might have arisen from domestic hot water systems, candles and battery-operated equipment, though these were not studied.

For the indoor conditions during the different seasons, three total internal heat gain values were used (winter, spring and summer values). Table 10 shows the daily average spans for the heat gains during different seasons and the yearly average.

Table 10 Seasonal and yearly averages of heat gain from occupants and household electricity (Bagge 2011)

	Occupancy /(W/m²)	Household electricity /(W/m²)	Total /(W/m²)
Year	1,7	5,3	7,1
Winter	2,1	6,6	8,7
Spring	1,8	5,2	7,0
Summer	1,2	4,1	5,3
Autumn	1,9	5,5	7,4

Following the requirements for the air flow in Building codes based on the type of room in residential buildings, the minimum air flow stipulated is 0.35 l/ ($m^2 \cdot s$) ,which means a specific air flow of $0.5h^{-1}$(Abel and Elmroth, 2007). This value was used for the estimation of the heat loss due to the ventilation of the room.

The temperatures considered for the inside environment of the apartment changes from 22°C to 27°C depending on the effects of the radiation. In winter, heating was needed if the indoor temperature (Ti) was lower than 22 °C while during summer the indoor temperature decreases 22° C for a few hours some nights. In the simulations, it was assumed that the heating system is not turned on unless the temperature decreases 19°C, otherwise cooling was needed in summer when the temperature inside was higher of 27°C.

Absorption and the delay of the temperature changes through the walls were not included in this project.

4.6 Results for solar gains

The energy balance is shown in the tables and graphics below. Solar gains for three different days, one in winter, another in spring and the last one for summer season are compared with needed energy for heating. The days were chosen because they show high values of solar radiation, therefore they represent sunny days, for example in Göteborg and Luleå the day selected was the 1st of February while in Stockholm was the 2nd of February. The net heating is positive if solar gain exceeds the heating requirements, for this case heating is not necessary by additional heat source, but maybe cooling it is required. When the solar gain is lower than heating requirements, a heat supply is needed.

The first case studied was Göteborg, considering one day in winter, one in spring and another one in summer. The U-values and g-values of the windows are as follows:

Table 11 U-values and g-values for the different windows used.

	U-value (W/m²·K)	g-value (-)
Window 1	0,78	0,32
Window 2	1,14	0,65

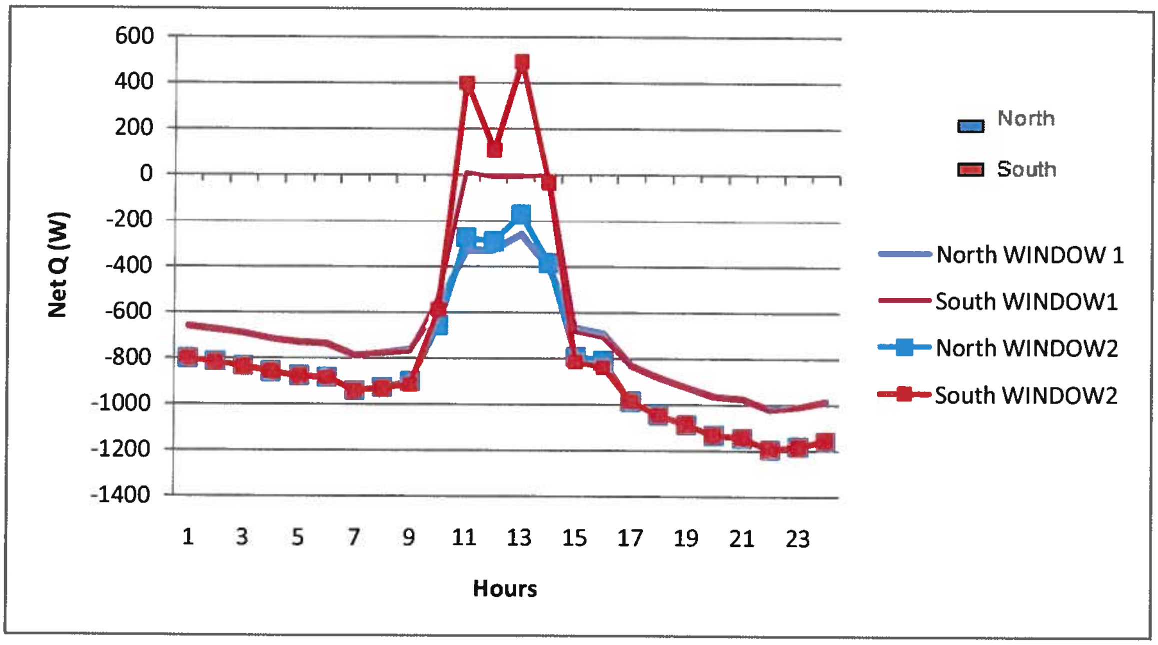


Figure 31 Energy balance winter, Göteborg

The graph from Figure 31 shows the information about the energy consumption for the case of 1st of February. The negative values show the heat needed to warm up the inside environment of the house. There are two peaks between 11 am and 13 pm in the windows 2 facing south due to the existence of clouds at that time. Between 11 am and 13 pm it is not necessary heating in the apartments with south facing windows. The window 1 presents most heating needed for most of the hours of the day, when the radiation is low. Heating needed for window 1 was required at 22 pm where 1022 W·h were needed for heating since at the same hour in the window 2 was 1195 W·h. For the whole day, window 1 facing north the heating needed was 17395 W·h/day and for window 2 was 20148 W·h/day, so the heating necessary will rise in almost 3000 W·h changing window 1 for window 2 (same case with windows facing south).

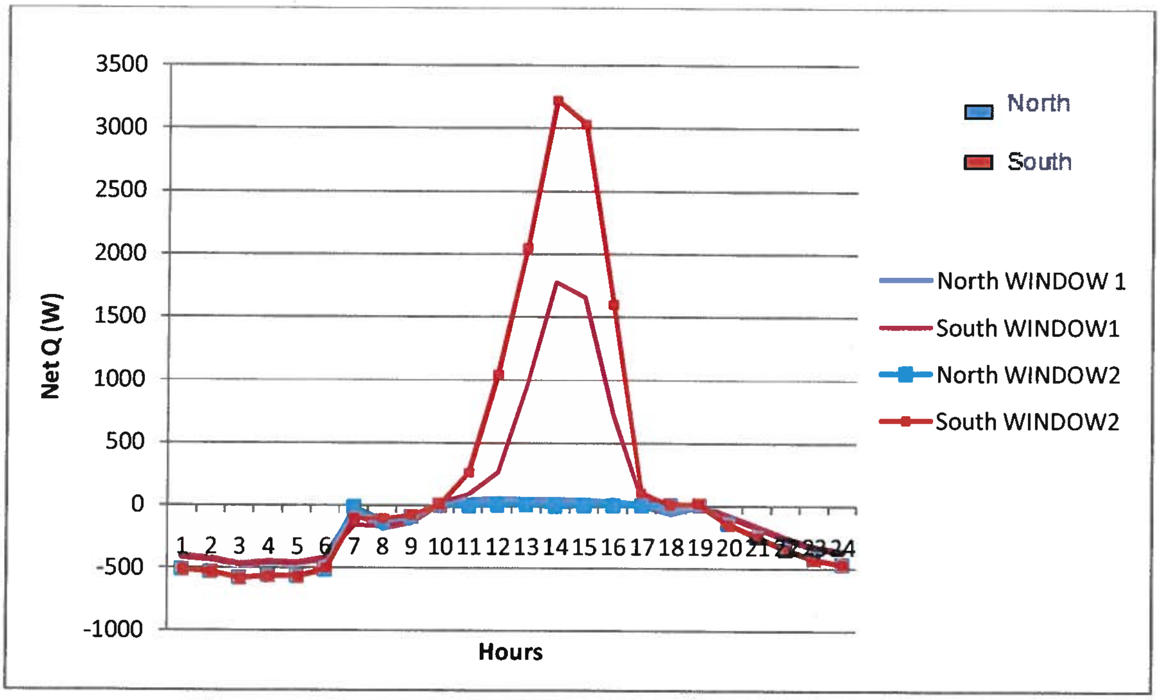


Figure 32 Energy balance spring, Göteborg

Moving now to the 1st of May, the solar radiation in this case takes more importance as it is higher and affects the window with higher g-value. The temperature considered for the inside environment of the apartment changes from 22°C to 27°C depending on the effects of the radiation. Window 2 needs some energy for cooling down the dwelling when the radiation is high enough. The window 1 presents lower heating energy needed for most of the hours of the day, when the radiation is low. In Window 1 facing north the heating needed for the 1st of May was 4347 W·h and for window 2 was 5189 W·h, so the heating necessary will rise in less than 1000 W·h changing window 1 for window 2. The bigger difference takes place for windows facing south where there is heating needed but also cooling. For example, in this case, for window 2 there is 5221 W·h/day needed but also 11335 W·h/day for cooling.

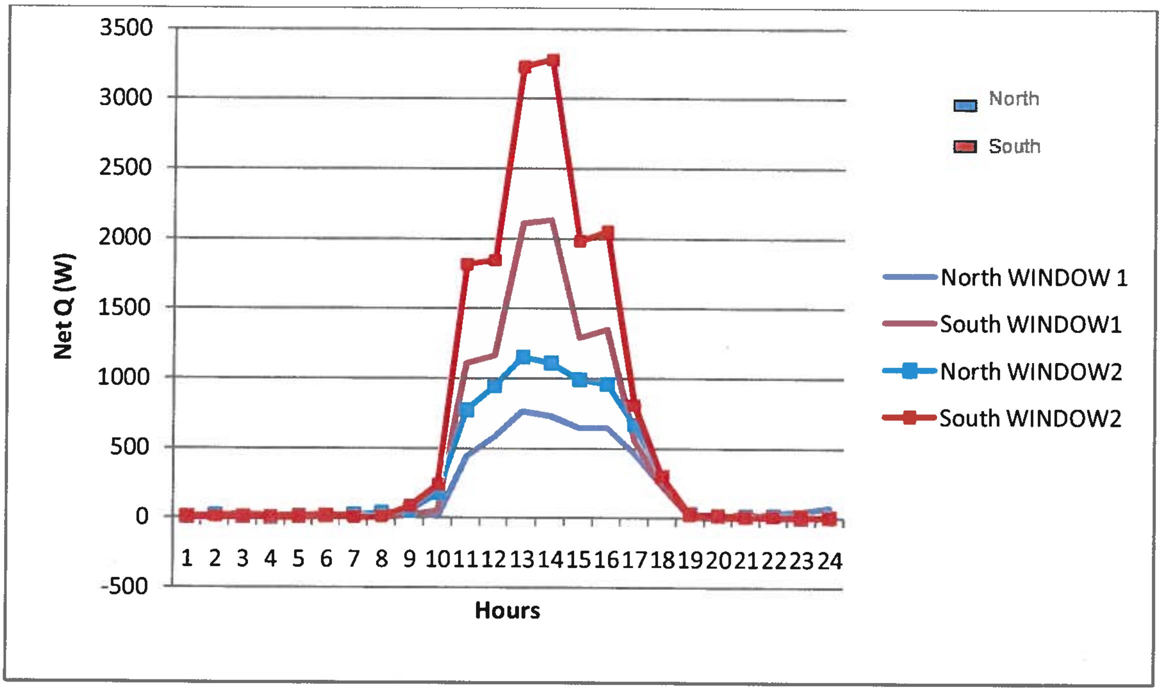


Figure 33 Energy balance summer, Göteborg

In the case of the 1st of August cooling is needed in the apartment during hours with high solar radiation. For window 2 the energy needed for cooling is much bigger than for window 1, so it does not optimize energy savings. During the summer the radiation is high so we want to have windows that can avoid overheating due to solar radiation. The worst case would be for the window 2 facing south where +15722.94 W would be needed for cooling.

The calculations shown in Figure 33, Figure 34 and Figure 35 are made for Stockholm climate.

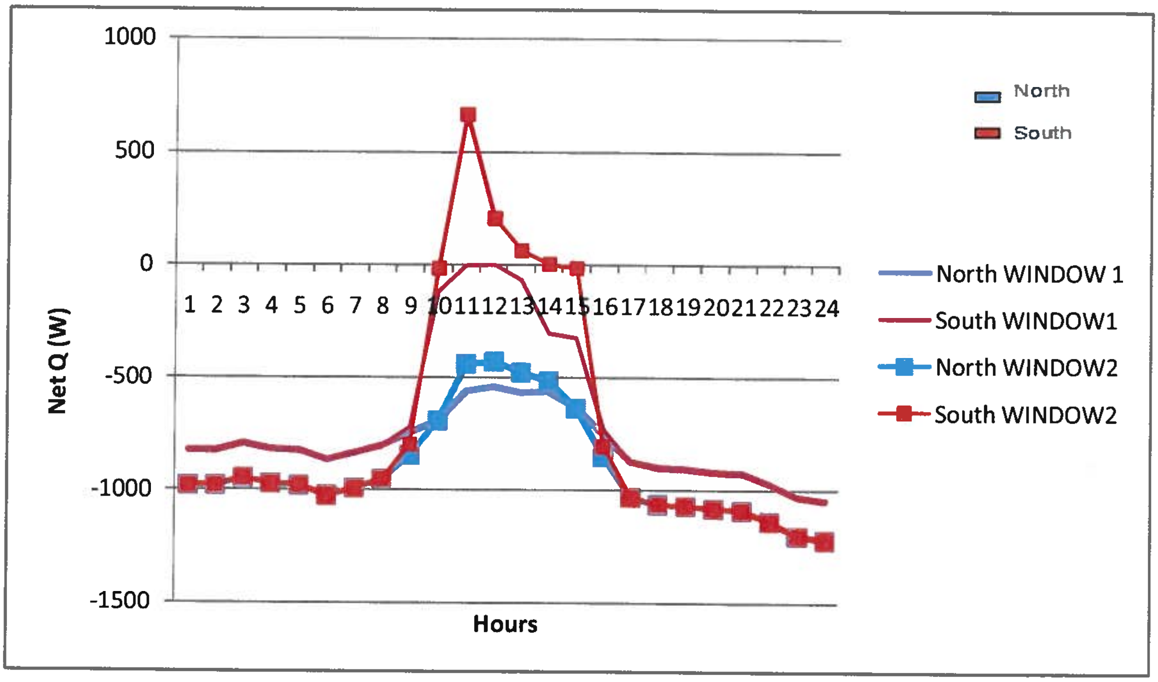


Figure 34 Energy balance winter, Stockholm

The graph from Figure 34 shows values obtained for the 2nd of February. In every case facing north heating is needed during the whole day. The window 2 facing south has a peak at 11am where solar radiation increase to 499 W. The window 1 presents lower heating energy needed for most of the hours of the day, when the radiation is low.

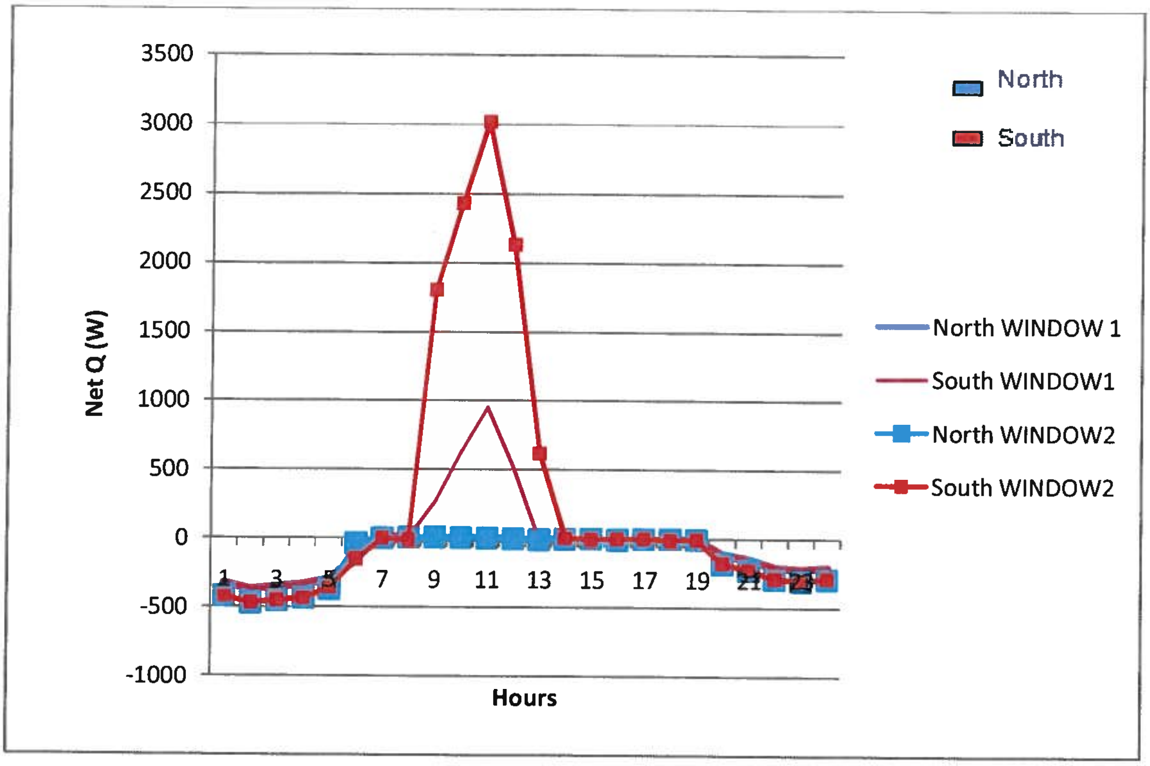


Figure 35 Energy balance spring, Stockholm

For the 3rd of May nor heating neither cooling is needed between 7am and 19pm for windows facing north. Between 19 pm and 5 am some heating is needed with every window, facing north and also south. The difference of cooling needed between window 1 and window 2 facing south, increases considerably between 9am and 13pm. The values obtained during night are rather similar to Göteborg for the 1st of May, since there is no solar radiation and the difference of temperatures was not big for days chosen. They also have many similarities during daylight. The biggest difference is that sun rise sooner in Stockholm but the sunset is also earlier.

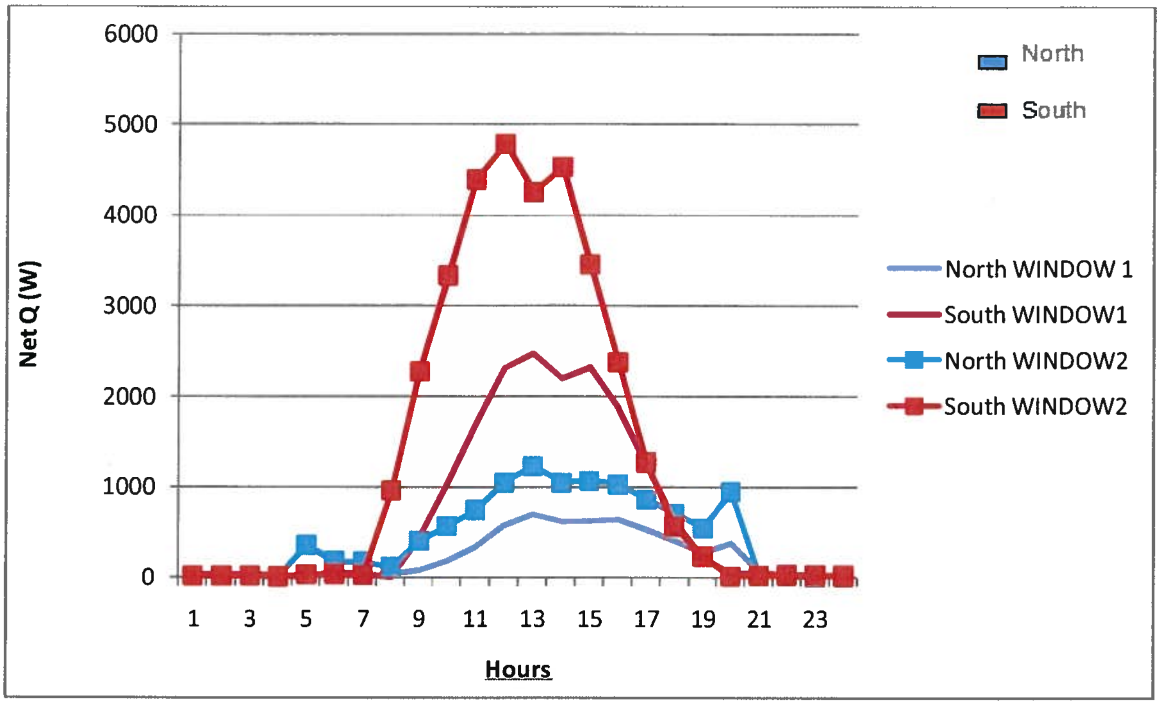


Figure 36 Energy balance summer, Stockholm

The 28th of July the difference is bigger for windows facing south. For window 1 less cooling is needed in both cases. Compared with Göteborg for the same season, the solar radiation in Stockholm is higher. The maximum solar radiation in Stockholm is at 12 am while in Göteborg is almost two hours later. The cooling needed for the window 1 facing south was 16878 W·h/day while with window 2 was 32718 W·h/day. Cooling is more expensive than heating and in this case, the difference changing the window means to double the cooling needed.

The last city where energy consumption was analyzed was Luleå.

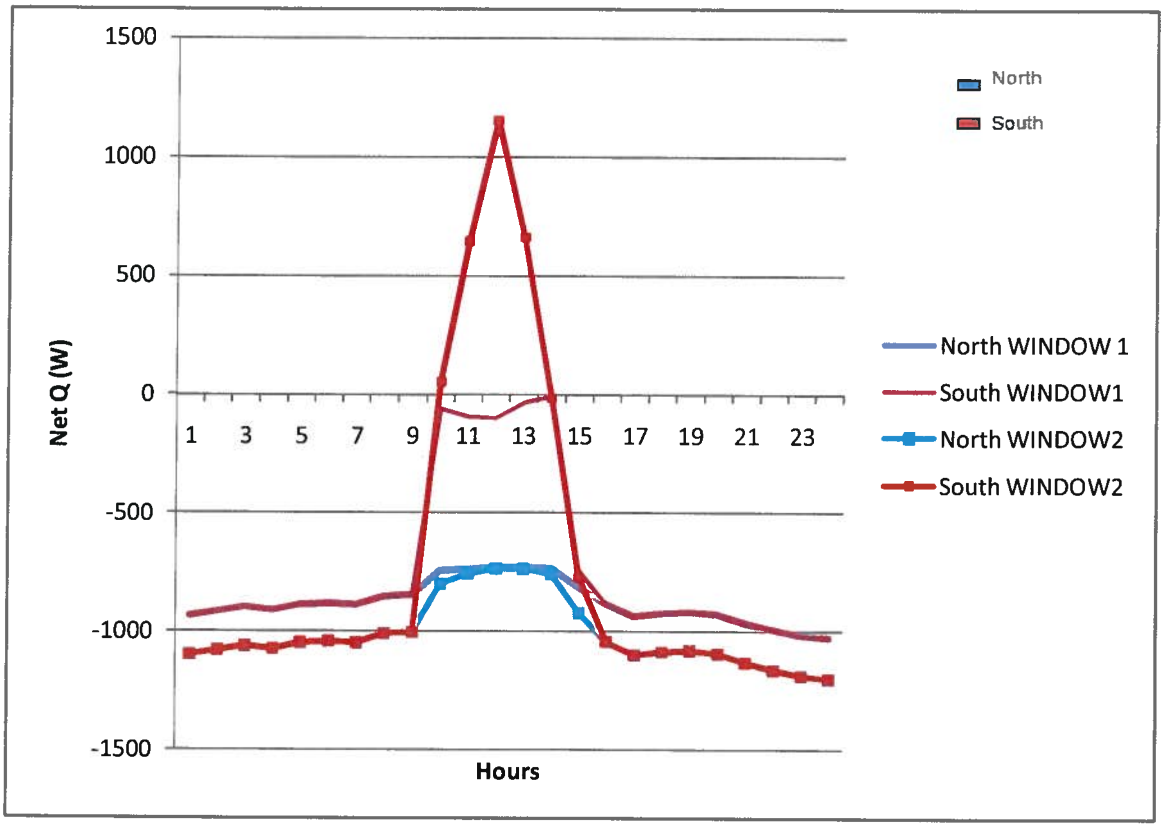


Figure 37 Energy balance winter, Luleå

The graph from Figure 37 shows that there is a great difference between windows facing north and facing south between 11 am and 13 pm, since only heating is needed for the windows facing north, while for windows facing south, in window 1 is almost not necessary heating and window 2 needs cooling during these 3 hours. As can be observed the graphics for winter season in Göteborg and Luleå are very similar due to the day used for the winter season was the 1^{st} of February which coincides with the day chosen in Göteborg. However, in Lulea the solar radiation would be lower at this time and also the temperatures outside, so especially more heating would be needed. While in Göteborg for window 1 facing north the heating needed was 17395 W·h/day, in Luleå the heating needed for the same window will be 21122 W·h/day. At the same time, the heating will rise in almost 3000 W·h changing window 1 for window 2 (same case that in Göteborg). The graph for Stockholm in winter has a lot of similarities with these two also, but the day chosen was one day after (2^{nd} of February), because the solar radiation for the 1^{st} of February was really low, probably due to it was a cloudy day in the city.

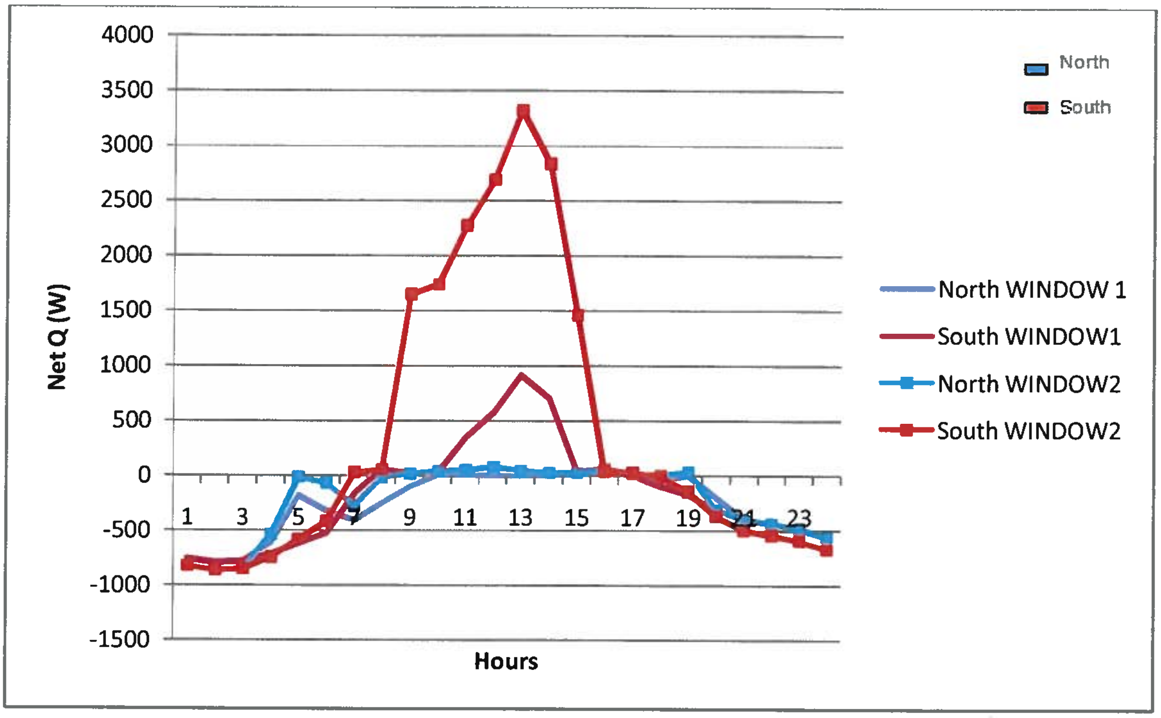


Figure 38 Energy balance spring, Luleå

The 1st of May was the day measured for spring calculations in Luleå (same as Göteborg and 2 days before than in Stockholm). There is a peak at 7 am in windows facing north due to the solar radiation decreased from 110 to 72 W/m^2 , and could be explain for the shadow created by clouds. The biggest difference, as in Göteborg and Stockholm, was between windows facing south. The heating needed for window 1 facing south was 6802 W·h, almost the same as for window 2 facing south that was 7098 W·h, but the problem is during the time that solar radiation is higher so while in window 1 the cooling needed was 2780 W·h , for window 2 was 16133 W·h/day.

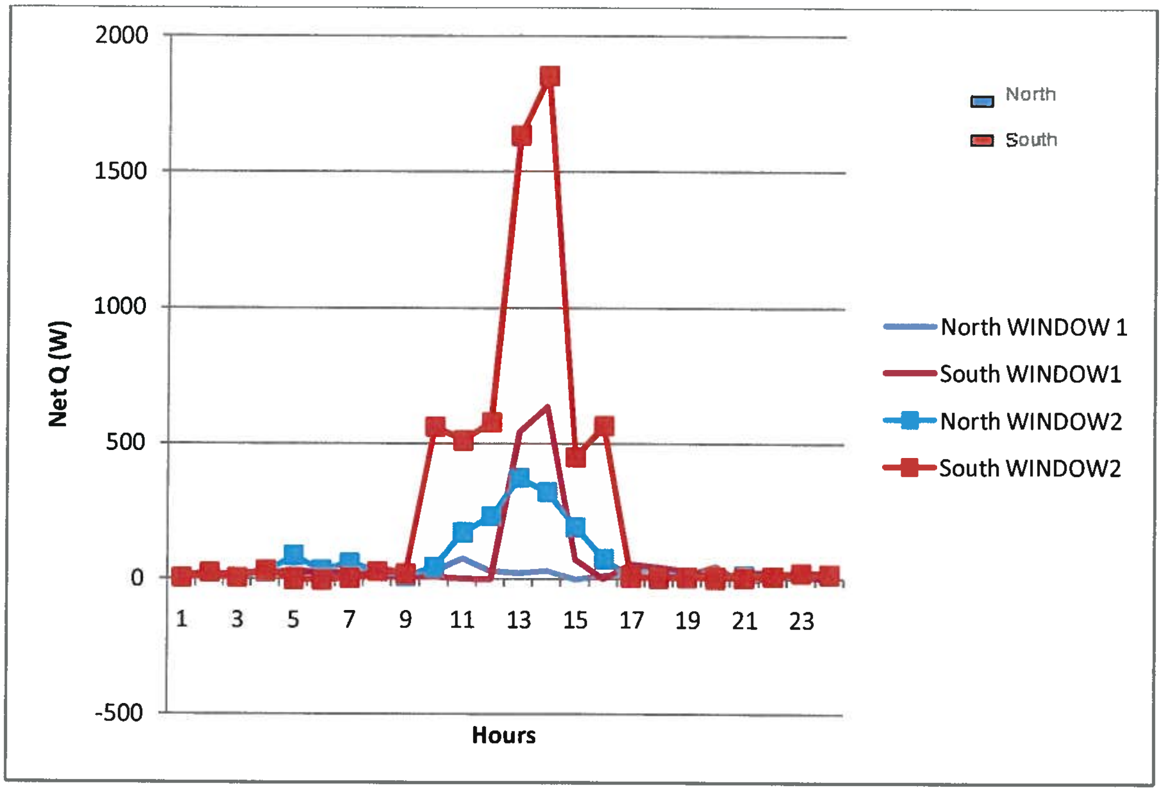


Figure 39 Energy balance summer, Luleå

Cooling needed for the 1st of August in Luleå is rather low, for windows facing south, in the first case the value obtained for the whole day was 1600 W·h and for the second case 6346 W·h.

There is a big difference between the values obtained for this graphic and the ones for Göteborg and Stockholm due to the maximum solar radiation registered was 369 W /m^2 at 14 pm south while in Stockholm for example for the 28th of July the maximum registered was 691 W /m^2 at 12 am.

4.7 Conclusions

In Table 12 it the main results obtained from energy calculations are shown.

Table 12 Summary of energy calculations

Dayly heating and cooling demand (kW·h/day)		Winter		Spring		Summer	
		Window 1	Window 2	Window 1	Window 2	Window 1	Window 2
Luleå North	Heating	-21122	-24267	-6321	-5644	0	0
	Cooling	0	0	84	432	487	1749
Luleå South	Heating	-17659	-17838	-6802	-7098	0	0
	Cooling	0	0	2780	16133	1600	6346
Stockholm North	Heating	-19200	-21602	-2756	-3511	0	0
	Cooling	0	0	18	15	5686	11180
Stockholm South	Heating	-16429	-18350	-2829	-3574	0	0
	Cooling	0	0	2373	10010	16878	32718
Göteborg North	Heating	-17395	-20148	-4347	-5191	0	0
	Cooling	0	0	241	12	4784	7288
Göteborg South	Heating	-16086	-19049	-4361	-5221	0	0
	Cooling	0	0	5560	11335	10050	15723

Finally the conclusion is that for Swedish climate the window with lower U-value and g-value has more advantages than the other one. Winter weather is longer than the others, so it is interesting to reduce the U-value as much as possible, even though the g-value is lower too.

On the other hand, for the warmest days windows with higher g-values would need more cooling energy supply as the solar radiation raises the temperature in the inside environment. The energy for cooling is more expensive that the one for heating. The cooling needed, can be reduced by opening the windows during summer.

5 Models for predictions and estimations of window's positions with respect to wall

A thermal bridge is a thermally conductive material which penetrates or bypasses an insulation system. When a window is placed in a wall, the connection between both creates a thermal bridge.

Construction materials are able to conduct heat easily, so despite of having insulating systems heat can still flow from one side to the other. However, the insulation of windows helps reducing these heat transfers. Thermal bridges could also form cold spots where condensation or mould could set. The used of cavity closures around the window frames reduces the effect of thermal bridging (Coxon 2011).

When an insulator is installed between framing, rather than exterior insulation, the framing acts as a thermal bridge. This is because the thermal conductivity of the frame materials is much higher than the insulation conductivity.

A thermal break is an insulation material placed next to a thermal bridge to reduce or stop the heat flow by increasing the thermal resistance. The thermal conductivity is the inverse of the thermal resistance, so if one of them is raised, the other one will decrease.

Thermal bridging can be a big problem especially in older houses, because they are less likely to be fitted with cavity walls and good insulations. For better results it is desirable to install PVC frames instead of wooden ones. See chapter 3 for more information about the frames.

5.1 Window´s connections to cavity walls

In the following figures, different positions of the windows with respect to the wall can be valued.

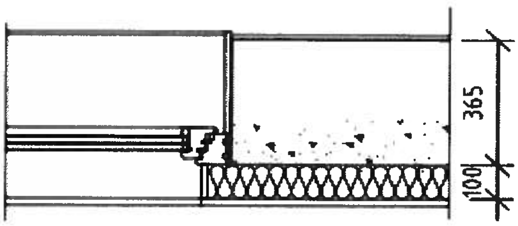


Figure 40 Window detailed concrete wall with frame insulation (wall type 1)

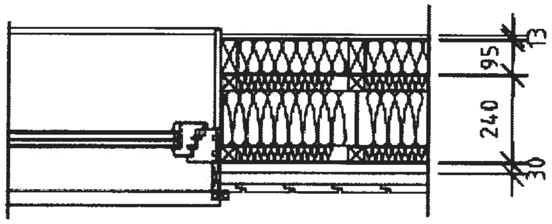


Figure 41 Window detailed passive-wooden wall without frame insulation (wall type 2)

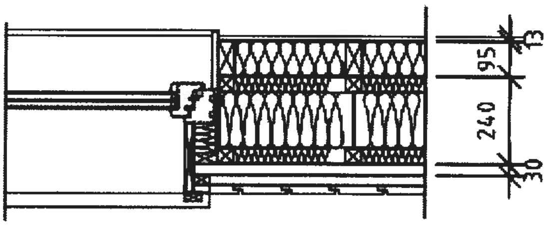


Figure 42 Window detailed passive-wooden wall with frame insulation (wall type 3)

5.2 Thermal bridge

In this section it is shown some designs for the windows and walls' structures chosen for the representation of the thermal bridges that take place in the junction between them.

5.2.1 Wall and windows distributions

The window chosen to be exposed in this section is the model 3 from Chapter 3, made of PVC and polyurethane foam insulations. This window has been selected because its frame showed the lowest U-value of all the models tested. However, the results of all the combinations of windows and walls are shown in the next section.

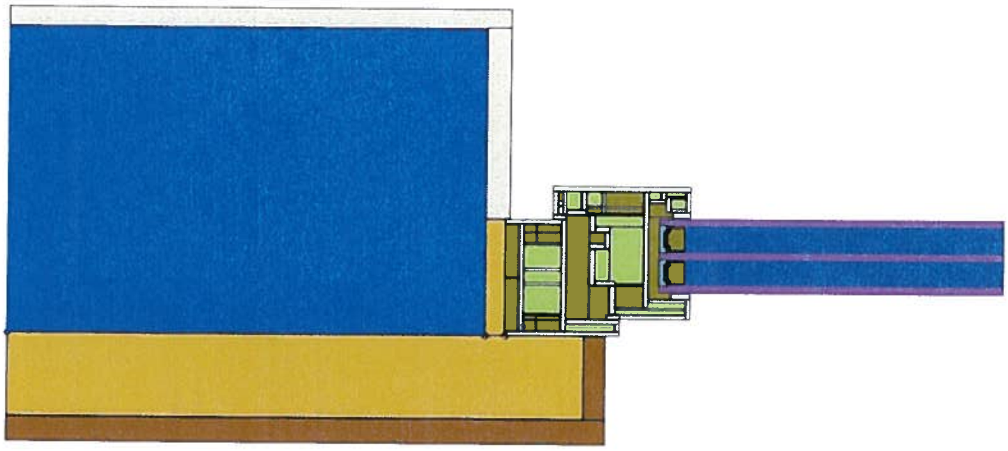


Figure 43 Thermal bridge for wall type 1

The main part of the wall is made of concrete (blue) with a thermal conductivity of 0.13 W/m·K, gypsum (white) with a thermal conductivity of 0.753 W/m·K, mineral wool (yellow) with a conductivity of 0.036 W/m·K and wood (brown) with a thermal conductivity of 0.014 W/m·K (Figure 43).

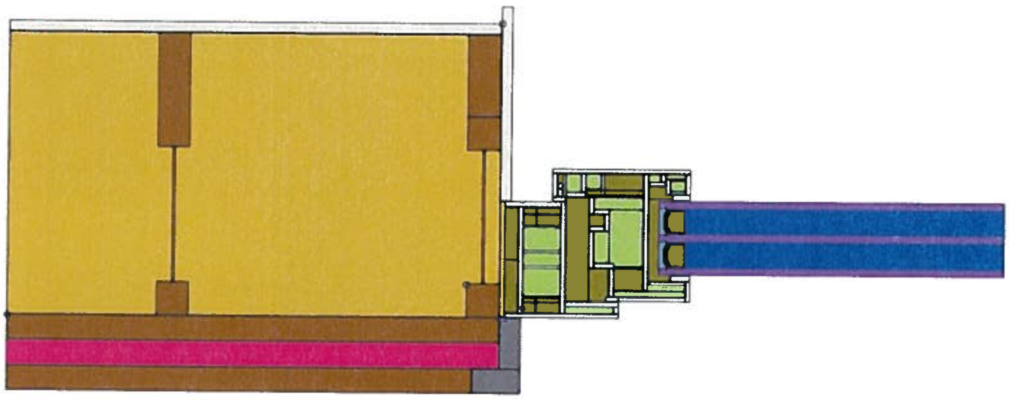


Figure 44 Thermal bridge for wall type 2

For the wooden walls the materials are the same than in the first wall but without the concrete part and with a little bit of steel (grey) with a conductivity of 50 W/m·K and a part of wall cavity (purple) with a conductivity of 0.27 W/m·K (Figure 44 and Figure 45).

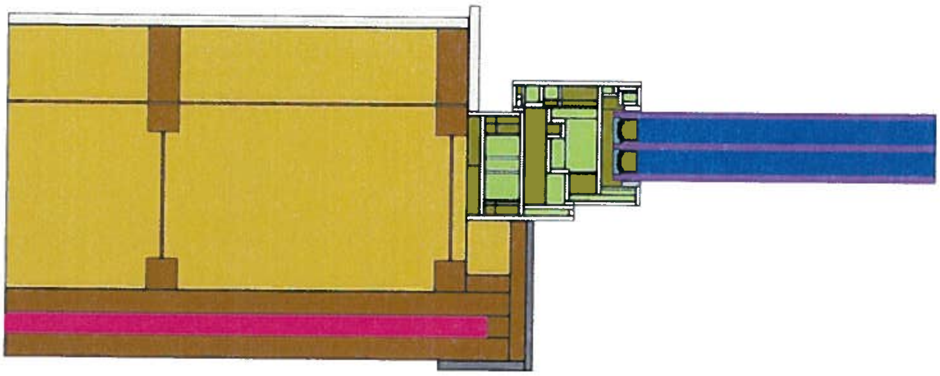


Figure 45 Thermal bridge with wall type 3

5.2.2 Calculations

In this section the calculations to obtain the results of the thermal bridges are described. The software HEAT 2 has been used for these calculations. The outside temperature has been considered 0°C, while for the inside one 20° C has been used. For the external surface resistance (R_{se}) 0.04 $m^2 \cdot K/W$ was considered and for the internal one (R_{si}) 0.13 $m^2 \cdot K/W$ was used. First it is shown the U-value of the wall used. In Figure 46 the dimensions used for the wall and the direction of the heat flow can be observed.

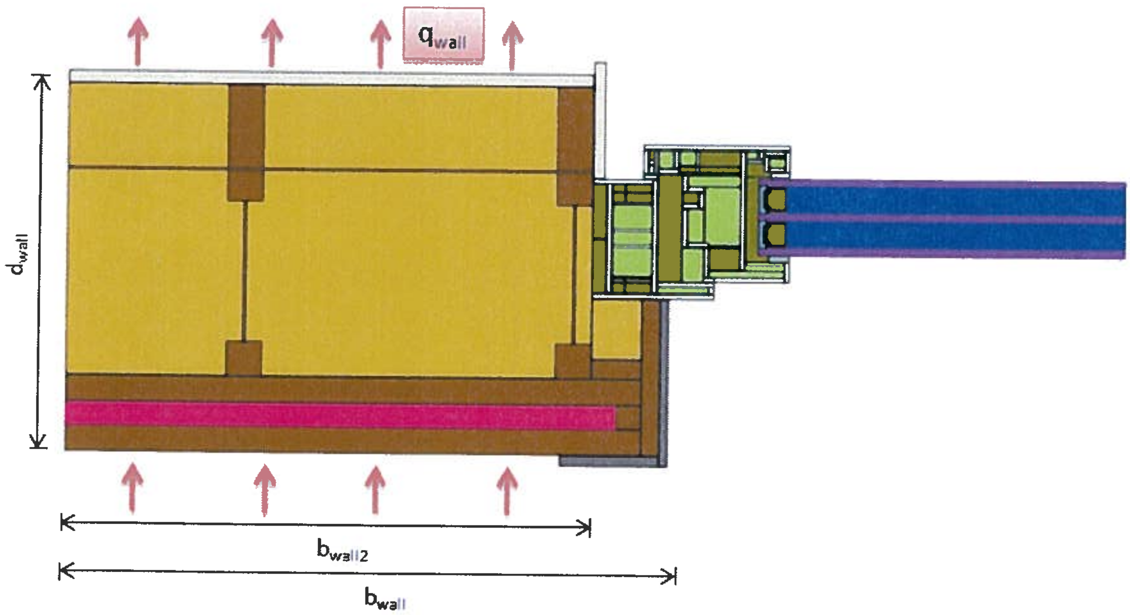


Figure 46 Dimensions and heat flow through the wall

$$U_{wall} = \frac{q_{wall}}{\Delta T \cdot b_{wall}} \qquad (20)$$

U_{wall} is the U-value of the wall ($W/m^2 \cdot K$)
q_{wall} is the heat flow through the wall (W/m)
ΔT is the difference in temperature between the inside and outside of the building (K)
b_{wall} is the length of the wall (m)

$$b_{wall} = 5 \cdot d_{wall} \qquad (21)$$

d_{wall} is the thickness of the wall (m)
Now it is shown the linear thermal transmittance.

$$L_{\Psi}^{2D} = \frac{q}{\Delta T} \qquad (22)$$

L_{Ψ}^{2D} is the thermal conductance of the combination of wall and window ($W/m \cdot K$)
q is the heat flow through the combination of wall and window (W/m)

$$\Psi = L_{\Psi}^{2D} - U_{wall} \cdot b_{wall2} - U_{window} \cdot b_{window} \qquad (23)$$

Ψ is the linear thermal transmittance between wall and window ($W/m \cdot K$)
b_{wall2} is the length of the wall without taking into account the frame insulation (m)
U_{window} is the U-value of the part of the window considered for the calculation ($W/ m^2 \cdot K$)
b_{window} is the length of the part of the window considered (m)

5.2.3 Results from calculations

In Tables 13 and 14 comparisons of obtained thermal bridges can be analyzed for all the combinations between the 3 types of walls mentioned before and the 9 types of windows from Chapter 3.

Table 13 Results from thermal bridges (Part 1)

Model	U-value window ($W/m^2 \cdot K$)	U-value wall ($W/m^2 \cdot K$)	psi-value ($W/m \cdot K$)
1.1) Aluminium and polyurethane foam frame on concrete wall	1,246	0,127	-0,012
1.2) Aluminium and polyurethane foam frame on wood wall without frame insulation	1,246	0,071	0,038
1.3) Aluminium and polyurethane foam frame on wood wall with frame insulation	1,246	0,07	0,034
2.1) Aluminium frame on concrete wall	1,438	0,127	-0,017
2.2) Aluminium frame on wood wall without frame insulation	1,438	0,071	0,035
2.3) Aluminium frame on wood wall with frame insulation	1,438	0,07	0,013
3.1) PVC and polyurethane foam on concrete wall	0,784	0,127	-0,0019
3.2) PVC and polyurethane foam on wood wall without frame insulation	0,784	0,071	0,019
3.3) PVC and polyurethane foam on wood wall with frame insulation	0,784	0,07	-0,014
4.1) Simple wood frame on concrete wall	0,81	0,127	-0,006
4.2) Simple wood frame on wood wall without frame insulation	0,81	0,071	0,017
4.3) Simple wood frame on wood wall with frame insulation	0,81	0,07	-0,0064

Table 14 Results from thermal bridges (Part 2)

Model	U-value window ($W/m^2 \cdot K$)	U-value wall ($W/m^2 \cdot K$)	psi-value ($W/m \cdot K$)
5.1) Aluminium frame with Super Spacer on concrete wall	1,399	0,127	0,029
5.2) Aluminium frame with Super Spacer on wood wall without frame insulation	1,399	0,071	0,035
5.3) Aluminium frame with Super Spacer on wood wall with frame insulation	1,399	0,07	0,03
6.1) PVC frame on concrete wall	1,136	0,127	-0,0085
6.2) PVC frame on wood wall without frame insulation	1,136	0,071	0,024
6.3) PVC frame on wood wall with frame insulation	1,136	0,07	-0,033
7.1) Cypress wood frame on concrete wall	0,8	0,127	-0,012
7.2) Cypress wood frame on wood wall without frame insulation	0,8	0,071	0,012
7.3) Cypress wood frame on wood wall with frame insulation	0,8	0,07	-0,0043
8.1) PVC and polyurethane foam frame with krypton on concrete wall	0,575	0,127	-0,0083
8.2) PVC and polyurethane foam frame with krypton on wood wall without frame insulation	0,575	0,071	0,011
8.3) PVC and polyurethane foam frame with krypton on wood wall with frame insulation	0,575	0,07	-0,014
9.1) Cypress wood frame with krypton on concrete wall	0,579	0,127	-0,01
9.2) Cypress wood frame with krypton on wood wall without frame insulation	0,579	0,071	0,014
9.3) Cypress wood frame with krypton on wood wall with frame insulation	0,579	0,07	0,0011

The results obtained from the thermal bridges correspond to the linear thermal transmittance (ψ-value), measured in W/m·K. This term, in our case, refers to the heat transmittance through the junction line between the window and the wall where this one is installed. It is often allowed to neglect punctual thermal bridges, so the conductance will be denoted L^{2D} because only two dimensional effects are considered.

The most interesting results are the lowest ones. For the wall made of wood and without frame insulation the results are worse than for the other walls in all cases. This is due to lack of insulation that reduces the effects of the thermal bridge. Without this insulation the connection is less insulated from environmental conditions, so it is normal than the results obtained for those cases are worse. The highest Ψ-value found (0.038 W/m·K) is for the combination of an aluminium and polyurethane foam frame with triple glazing and argon filling and a wooden wall without frame insulation.

In general the lowest Ψ-values are obtained for the concrete wall with frame insulation. This is due to the low insulation of the material mainly used for the construction of this kind of wall. Therefore the heat transmittance between the wall and the window is lower. There are just three cases when the value is lower for the wooden wall with frame insulation. These cases are the combination of wall and windows' models 3, 7 and 9, one with PVC and polyurethane foam and the others with wood frames.

In Figure 46 the results are shown graphically, so it is easier to compare the different Ψ-values for the combinations studied.

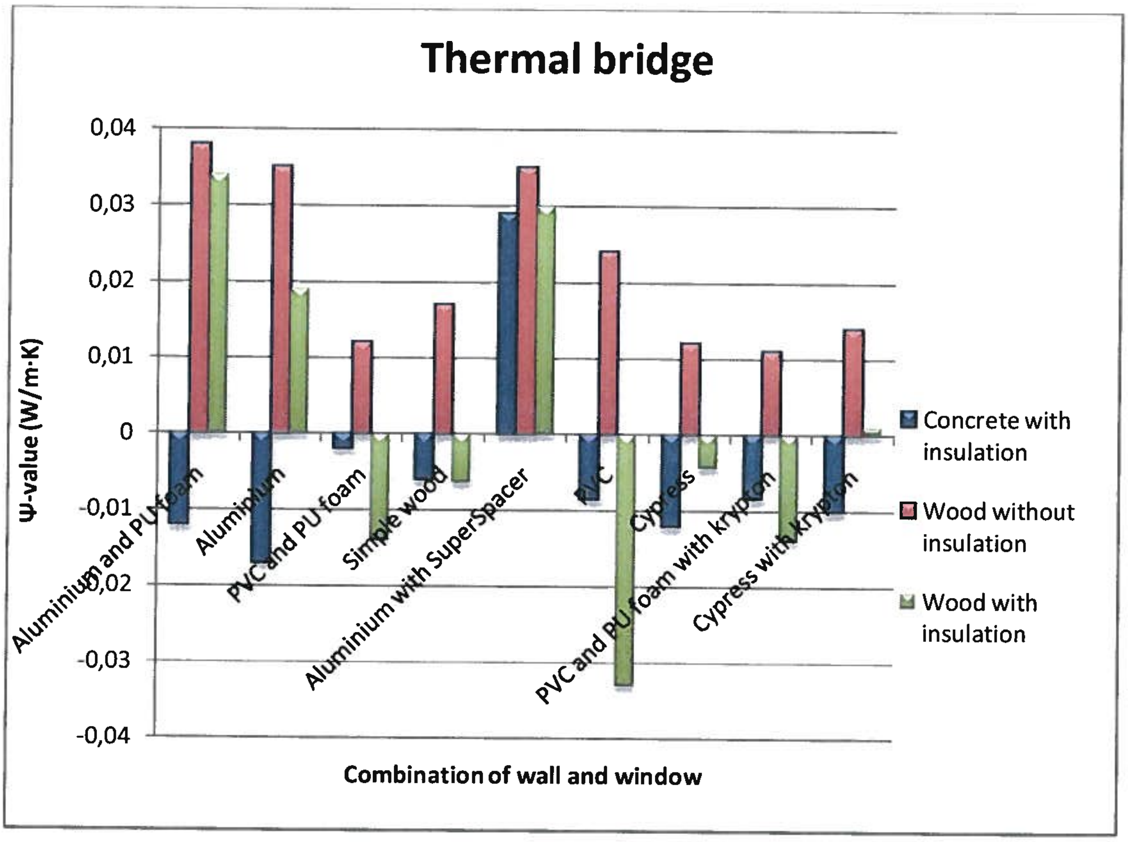


Figure 47 Graph of the results of thermal bridge

The negative values of the thermal bridges are obtained because the insulation of the edge is good. This means that there is not extra heat loss but a heat gain according to the extra frame insulation. So, it is observed that the thermal bridge between wall and window can be minized, even obtaining a Ψ-value of zero. In Figure 47 it can be observed that the lowest value of the thermal bridge have been measured for the combination of PVC and polyurethane foam frame and wood wall with insulation (-0.033 W/m·K).

To conclude with thermal bridge results it is important to comment that the best option for the wall is to have frame insulation. The problem is that the application of this insulation could have negative impact if the drainage is not good enough. The rain could affect the part marked in the next figure, appearing mould and damaging the whole structure of the wall. For this reason this kind of walls are more difficult to apply and therefore less common to see in construction.

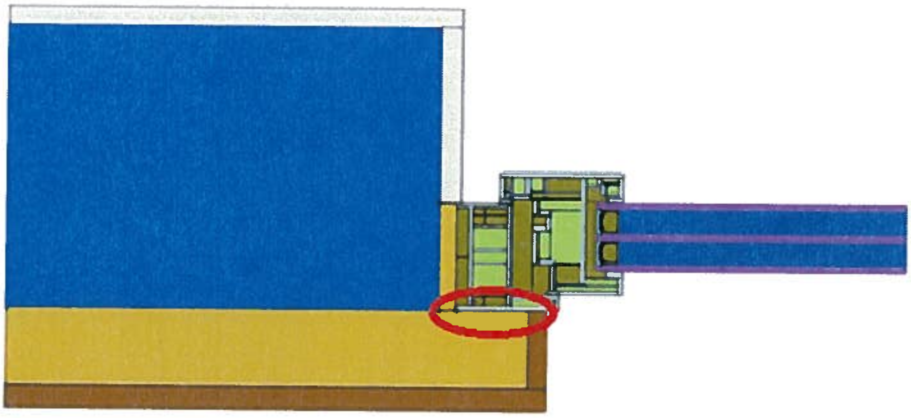


Figure 48 Section where the wall could be damaged

6 Evaluation of the tightness and installation process

The main objectives of a window are to allow daylight to penetrate in the room and to provide a view out, as well as ventilation in the case of openable windows. As a part of the external enclosure, they are the junction between the interior and exterior of the house, reason why they must fulfill the following functions:

Heat and cold protection.

Rain and snow protection.

Wind protection.

Safety (fire and burglary protection, among others).

Sound insulation.

6.1 Airtight

Air leakages contribute to ventilation, heating and cooling costs and moisture migration, making air tightness a key property in buildings. Up to a 50% of a whole building leakage can happen on the windows, while other air leaks normally occur on doors, vertical shafts and building envelope (Sherman and Chan 2004). There is a direct connection between an airtight building and the energy consumption for heating, as air leaks increase building's heat loss, affect the moisture level and thermal comfort, increase the risk of condensation and deteriorate sound insulation, reason why they should be eliminated. Normally, fixed-pane windows are the most airtight and least expensive window frames, while openable windows such as single-hung windows and sliding windows are more inefficient due to a higher rate of air leakage (Hacker and Gorges 1998).

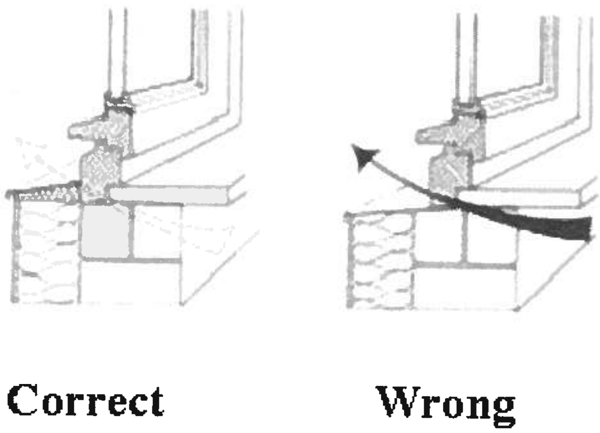


Figure 49 Correct and wrong installation (Paula 2011)

There are different methods to prevent air leakages, for example by placing draught excluders or a weather strip between frame and sash. Draught excluders also serve as a vapour barrier, and have to be placed on the inner part of the window to prevent humid air to enter and to prevent moisture and humid air going between the window panes, resulting in condensation on the inside of the cold outer pane. The weather strip must be effective but at the same time it has to allow freedom of movement to the window to open and close easily, as it can be observed in Figure 50. It must be selected according to the friction, wear, weather and temperature changes associated with its location, guaranteeing that it is securely fixed and that the joint will maintain its airtight properties during the lifetime and is not damaged or decomposed during the service life. It is also useful to place a dust-absorbing strip to allow more ventilation and reduce dirt accumulation.

Window manufacturers carry out air permeability tests according to the respective standard to proof and classify the airtightness of their windows. Nevertheless, most of the air leakages on the windows are due to bad installation during construction of the windows, as it will explained later.

A good practice to reduce air leaks is the addition of storm windows, which can reduce the heat loss of a window by 60% to 80% (Sherman and Chan 2004). Storm windows act as a second layer of window, reducing the air movement in and out of the existing windows. They keep out wind and cold in the winter and heat in the summer, giving an extra barrier and helping insulating the home (Window Guide 2010).

There are other important sources of air leakage, such as cracks along the top edge of the windows or the called "extraneous air leakages" from window perimeters, which are often higher than the air leakage through the window unit. The extraneous air leakages occur in the joint between window and wall assemblies or from the sides of the windows, and are not measured in the current window testing standards. They can be significant through some types of window installed assemblies, affecting the overall performance of the window by letting air passing around the perimeter of the window frame, leaking air from cavities into the building through openings in the window frame or through the interior trim. As a consequence, despite the window can be considered as airtight by the standards, the whole assembly (including its perimeter joints) can be highly air permeable once installed, which leads to condensation, energy loss and excessive drafts (Louis and Nelson 1995). A good practice to reduce extraneous air leakages is using sealing methods such as poly-return, poly-wrap, foamed-in-place urethane or casing tape (Sherman and Chan 2004).

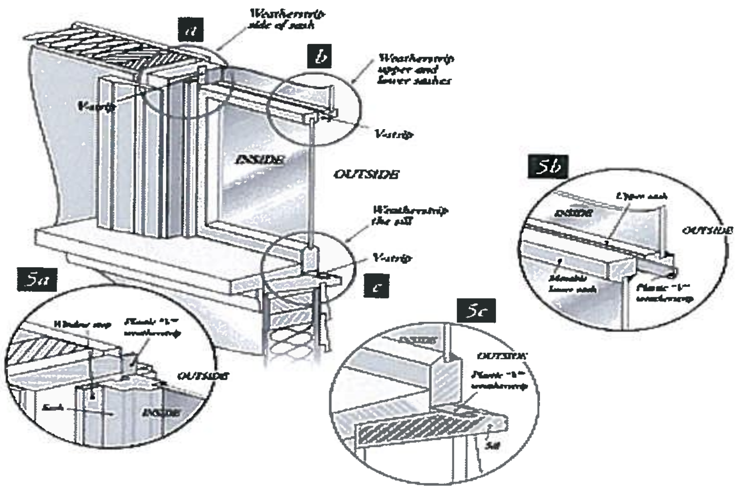


Figure 50 Where to weatherstrip a single-hung window (Natural Resources Canada 2001)

As it has been observed, airtightness is an important factor that has to be considered during the design and construction stages of the window and building. A good practice in order to improve the airtightness of a building would be undertaking an air permeability test once the building is near to be finished, which results show if the building passes or fails the required airtightness standard. If the building does not meet the required results, further inspections should be undertaken using tracer smoke that helps identifying areas of great heat loss (Sustainable Energy Ireland 2008). Another common method to locate air leaks is the use of thermographic equipment, as it is shown on Figure 51.

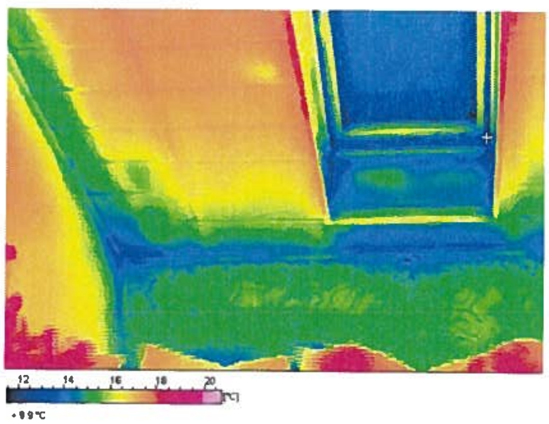


Figure 51 Temperature changes around the window and corners of the building (Sustainable Energy Ireland 2008)

6.2 Humidity

Humidity in the air can be described as absolute or relative. If relative humidity is used, then the relative humidity changes with temperature and decreases with increasing temperature. The relative humidity is an important factor in Sweden, as it is usually high, so it is really important to prevent it.

Condensation occurs when moist air comes into contact with cool surfaces, such as glass. This type of condensation appears when the dew point in the air is higher than the temperature of the glass. This occurs when a cool night follows a warmer day, most typically during the spring and fall seasons.

The risk of mould growth on the corners, as it is shown in Figure 51, can be increased by the presence of air penetration on the inside of the room. In winter, when the water vapour content in the outdoor air is low, the cold air enters the heated room inside the building and is heated up. Consequently, the relative humidity of the indoor air decreases. The indoors air is increased by the occupants and its day-a-day activities, like cooking or washing, so that it contains more vapour than the air outdoors. When the air leaks into the building envelope, it decreases in temperature and increases in relative humidity, so it sometimes condense within the insulation, increasing the moisture content and increasing the risk of mould growth and decomposition of the building. The key factor is building airtight buildings but also ventilate them thanks to controlled vents. By doing this, moisture and polluted air can be extracted from the inside. Therefore, it is necessary to guarantee a controlled air change in order to maintain the relative humidity indoors at acceptable levels (Rasmussen 2009).

6.3 Rain and snow protection

When designing a window, it is important to make sure that the water is drained to the outer of the window. Also, the constructive design of the frame must protect this from rain and snow penetration. One example is the application of grooves in order to reduce pressure differences as it is shown in the next figure.

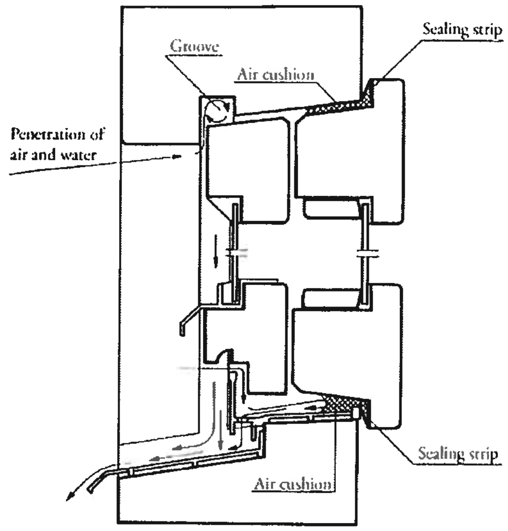


Figure 52 Groove to reduce pressure difference and to drain rain water (Bülow-Hübe 2001)

Water tightness is defined as the ability of a closed window to resist water penetration, considering water penetration as the continuous wetting inside of the woodwork or in part that are not designed to be wet, when water drains to the outside. In order to proof the water tightness, water permeability tests are undertaken by the constructor of the window to guarantee that it fulfils the requirements, according to standards (CIDEMCO 2004).

6.4 Wind protection

Resistance to wind load is especially important in windows located in high buildings on exposed facades, where wind pressures are considerable. In order to proof the wind load resistance of a window, window manufacturers have to undertake a series of tests to proof the suitability of the window under different load circumstances. These tests usually are:

Strain test: proves that the complete window has an admissible deformation.

Repeated pressure test: shows that the window conserves its properties.

Safety test: guarantees safety of the users.

6.5 Noise protection

Windows are the weakest element of a building regarding acoustic insulation. A bad window can ruin the acoustic protection of a proper construction, reason why it is important to choose an appropriate design and materials for the frame and glaze, as well as a good installation. The sound insulation of a window is defined as the capacity of this to reduce the sound pressure from an external source and is normally expressed in decibels (dB).

If an optimal noise protection is desired, there are three main aspects to take into account:

Opening system

Openable windows protect less from noise than fixed windows. Nevertheless, hung windows perform better than sliding windows, so this type of openable windows should be installed when an openable window with good acoustic protection is needed.

Airtigth

As it has been said before, air leaks affect sound insulation, since sound waves are transmitted on the air. Therefore, air leaks should be avoided to prevent undesired noises.

Glazing and frame design and materials

Selecting an appropriate glaze is one of the most important factors for sound insulation, depending largely on the thickness of the glass. Air gaps offer an excellent thermal protection, but the noise protection is not always improved. For example, despite it may seem strange, the insulation of a 4/12/4 glass is not always better than the one of a simple 4 mm glass. When selecting the glaze, if high acoustic insulation is desired, at least one of the glasses should be more than 6 mm thick. Also, if the air gap is filled with noble gases, the acoustic performance of the windows is usually improved. On the other hand, different materials respond differently to airwaves, so the selection of both glaze and frame materials are an important aspect to consider.

7 Summary and conclusions

The aim of this work was to develop windows in a way that energy efficiency is maximized. Finding the best option for insulating the windows will allow windows to save in energy consumption. The goal of this thesis was to present the necessary improvements to reach this aim.

The field where this new concept was wanted to be introduced is related to passive-houses and zero-net energy buildings. However, this product can be beneficial for a wide range of markets, because it is interesting for everyone who wants to save energy and therefore money. So its use could be considered for any kind of public either private building.

The work was divided in different steps. The first step was a literature review. In this way valuable information from projects developed in other universities and companies was found.

The second step was to design insulating windows in order to minimize the heat transfer through them. There were two well differentiated parts to take into account. The first one was the frame, which is the most critical one. It was a rough work to design the proper one to try to avoid the heat flow as much as possible. The other one was the glazing part of the window. This one was quite easier, as we just needed to investigate different materials and gases we wanted to use for the glazing part and spaces between them. The software HEAT 2, 7.1 was chosen for this purpose.

The next subject we took care of was the solar radiation through the window glass. The aim of this part was to compare the effects of this radiation for windows with different g-values. The studies were focused in the effects of the Sun to the inside environment of the building. For these calculations the softwares WINDOW 6 and METEONORM were used.

In order to show the effects of the combination between g-value and U-value the energy consumption of an apartment was calculated regarding these values. The climate of three different cities of Sweden (Stockholm, Göteborg and Luleå) and three different seasons of the year (winter, spring and summer) were used for the calculations. The apartment was considered in two different ways, one with the only window of the room facing south and the other one with the only window of the room facing north.

Following with the work, the thermal bridge that takes place in the joint where the window is mounted in the wall was calculated. For this issue the software HEAT 2, 7.1 was used again. The main purpose of this section was to minimize the values for the linear thermal transmittance that occurs between the window and the wall where it is installed.

Finally, the last step was to present specifications of different installation procedures for sealants in order to counteract the rain and air effects coming from the outside environment conditions. For this, literature review and drawings have been used.

Now we will show the main conclusions we have considered from the work done during the development of the whole thesis. Designing windows is a laborious work due to all factors that affect this part of the building. We do not need just to avoid heat loss, but take into account solar radiation along with other properties needed for the proper functioning of windows.

First thing we want to talk about is the improvement that the use of a fictitious material carries for the decreasing of the U-value of the frame. The thermal conductivity of this material is lower than the ones considered before for the construction of windows, in order to avoid effects of thermal transmittance. Evaluating this improvement and comparing with the ones shown for changes in the dimensions and shapes of these frames, we think that further investigations to get better U-values of windows should focus on developing these materials. They should have lower thermal conductivities than the current materials but keeping the structural properties needed to fulfil their function.

Another development was noticed when the glass was substituted by polycarbonates materials. The improvement of the U-value was minimal, however the decreased of the thermal bridge between glazing and frame was more important. This is due to the low thermal conductivities of polycarbonates that imply a good value for the linear thermal transmittance between the frame and these materials.

If we continue treating the glazing part of the window, the decrease of U-value in this part is higher when we change the material in the space between the panes, than changing the panes themselves. In this line we conclude that the use of vacuum or aerogel in the filling of these spaces would improve the values of the whole window. Further work should concentrate on developing installation processes for reaching vacuum conditions in the spaces and also on finding a more transparent solution for aerogel materials.

Another conclusion is the use of blinds. An investigation of how much the use of a blind can decrease the U-value was made. It is important that the U-value of the window before the installation of this system is low enough so that no condensation appears in the inside of the window. The reduction of the U-value due to the use of blinds was close to 19% for a window with a U-value of 0.784 $W/m^2 \cdot K$.

Moving forward to energy consumption of an apartment, we have to take into account that the U-value and g-value are directly proportional. This means that when the U-value is low the g-value is also low. A low g-value implies little solar gains. It was observed that the window with a lower U-value and g-value usually shows the best conditions for saving energy. During the winter, that is the longest season in Scandinavian climate, the energy consumption for heating is lower for the window with a lower U-value. And when the weather is warm, the apartment needs more cooling energy for the window that has a higher g-value. In this case the energy saving is even more important because the energy use for cooling is more expensive that the one for heating. The values of energy calculations are shown in Table.

Table 15 Summary of energy calculations

Dayly heating and cooling demand (kW·h/day)		**Winter**		**Spring**		**Summer**	
		Window 1	Window 2	Window 1	Window 2	Window 1	Window 2
Luleå North	Heating	-21122	-24267	-6321	-5644	0	0
	Cooling	0	0	84	432	487	1749
Luleå South	Heating	-17659	-17838	-6802	-7098	0	0
	Cooling	0	0	2780	16133	1600	6346
Stockholm North	Heating	-19200	-21602	-2756	-3511	0	0
	Cooling	0	0	18	15	5686	11180
Stockholm South	Heating	-16429	-18350	-2829	-3574	0	0
	Cooling	0	0	2373	10010	16878	32718
Göteborg North	Heating	-17395	-20148	-4347	-5191	0	0
	Cooling	0	0	241	12	4784	7288
Göteborg South	Heating	-16086	-19049	-4361	-5221	0	0
	Cooling	0	0	5560	11335	10050	15723

A thermal bridge is a thermally conductive material which penetrates or bypasses an insulation system. The conclusion we want to express for the thermal bridge between wall and frame is that the best values are obtained for those walls that have frame insulation. And they are even better if the wall is made of concrete instead of wood. This is because the flange part of the wall is mainly made of concrete, what makes it not very insulated. Then, the thermal bridge between the frame part of the window and the place of the wall where it is installed is low and in most of the cases below zero, which means that there is not heat loss but heat gain, due to the extra frame insulation. These negative values make us think that the value of the thermal bridge could be minimized even reaching a value of zero.

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9 Appendix

Data solar radiation Göteborg:

	WINTER-1February			SPRING-2May			SUMMER-1August		
Hour	Tamb (°C)	Global solar radiation North (W/m²)	Global solar radiation South (W/m²)	Tamb (°C)	Global solar radiation North (W/m²)	Global solar radiation South (W/m²)	Tamb (°C)	Global solar radiation North (W/m²)	Global solar radiation South (W/m²)
1	-4,4	0	0	2,8	0	0	16	0	0
2	-4,6	0	0	2,5	0	0	16,1	0	0
3	-4,9	0	0	1,7	0	0	16,2	0	0
4	-5,3	0	0	2	0	0	16,1	0	0
5	-5,6	0	0	1,9	0	0	16,6	42	12
6	-5,7	0	0	2,2	5	7	16,9	80	39
7	-6,6	0	0	2,1	89	67	16,7	31	31
8	-6,4	0	0	1,9	65	68	17,2	29	29
9	-6,5	5	3	3	60	62	17,5	77	81
10	-4,9	26	36	4,5	115	142	17,9	89	98
11	-4,9	82	425	5,7	150	265	19,1	158	311
12	-4,1	72	254	6,4	165	369	20,2	166	298
13	-4,4	92	431	7,5	171	500	21,7	173	478
14	-4,8	65	165	9,7	149	638	21,5	170	489
15	-5,1	8	5	9,9	130	607	21,4	154	300
16	-5,8	12	8	9,7	120	400	21,9	142	302
17	-7,3	0	0	10,2	101	172	22,1	96	117
18	-8,2	0	0	9,8	58	58	22,2	40	40
19	-8,9	0	0	9,3	84	37	21,1	16	17
20	-9,6	0	0	7,9	7	7	19,4	16	15
21	-9,8	0	0	7	0	0	18,5	0	0
22	-10,6	0	0	5,4	0	0	17,4	0	0
23	-10,4	0	0	4,2	0	0	16,6	0	0
24	-10	0	0	3,5	0	0	16,1	0	0

Winter Göteborg:

Hour	North WINDOW 1 (W·h)	South WINDOW 1 (W·h)	North WINDOW 2 (W·h)	South WINDOW 2 (W·h)
1	-663	-663	-802	-802
2	-674	-674	-815	-815
3	-692	-692	-834	-834
4	-715	-715	-859	-859
5	-732	-732	-878	-878
6	-738	-738	-884	-884
7	-790	-790	-941	-941
8	-779	-779	-929	-929
9	-762	-771	-901	-914
10	-577	-533	-656	-588
11	-330	10	-275	402
12	-328	-12	-292	108
13	-257	-7	-175	496
14	-399	-1	-384	-34
15	-668	-681	-792	-812
16	-691	-709	-809	-836
17	-831	-831	-986	-986
18	-883	-883	-1043	-1043
19	-924	-924	-1087	-1087
20	-964	-964	-1131	-1131
21	-976	-976	-1144	-1144
22	-1022	-1022	-1195	-1195
23	-1011	-1011	-1182	-1182
24	-988	-988	-1157	-1157
Total heating (W·h/day)	**-17395**	**-16086**	**-20148**	**-19049**

Spring Göteborg:

Hour	North WINDOW 1 (W·h)	South WINDOW 1 (W·h)	North WINDOW 2 (W·h)	South WINDOW 2 (W·h)
1	-415	-415	-516	-516
2	-432	-432	-535	-535
3	-478	-478	-586	-586
4	-461	-461	-567	-567
5	-467	-467	-573	-573
6	-427	-419	-520	-506
7	-63	-160	-17	-103
8	-180	-167	-130	-109
9	-139	-130	-94	-81
10	17	19	-4	6
11	35	92	-3	260
12	47	261	-1	1043
13	43	949	6	2052
14	44	1777	-7	3225
15	32	1660	-1	3035
16	20	728	-1	1602
17	3	57	-1	100
18	-55	15	4	5
19	0	-3	3	9
20	-88	-88	-145	-145
21	-171	-171	-250	-250
22	-264	-264	-351	-351
23	-333	-333	-427	-427
24	-374	-374	-472	-472
Total heating (W·h/day)	**-4347**	**-4361**	**-5191**	**-5221**
Total cooling (W·h/day)	**241**	**5560**	**12**	**11335**

Summer Göteborg:

Hour	North WINDOW 1 (W·h)	South WINDOW 1 (W·h)	North WINDOW 2 (W·h)	South WINDOW 2 (W·h)
1	8	0	3	3
2	13	-2	16	3
3	19	4	3	3
4	13	-2	-2	3
5	11	-2	9	1
6	24	5	10	11
7	8	9	20	0
8	6	-2	33	4
9	37	15	53	80
10	10	50	177	238
11	434	1108	774	1817
12	580	1161	944	1844
13	761	2105	1150	3230
14	728	2133	1109	3284
15	647	1290	989	1985
16	644	1349	960	2051
17	462	554	668	811
18	225	225	296	296
19	9	14	32	23
20	-1	-5	17	20
21	1	37	10	2
22	31	-3	17	4
23	42	1	-2	5
24	71	5	3	3
Total cooling (W·h/day)	**4784**	**10050**	**7288**	**15723**

Data solar radiation Stockholm:

	WINTER-2February			SPRING-3May			SUMMER-28July		
Hour	Tamb (°C)	Global solar radiation North (W/m²)	Global solar radiation South (W/m²)	Tamb (°C)	Global solar radiation North (W/m²)	Global solar radiation South (W/m²)	Tamb (°C)	Global solar radiation North (W/m²)	Global solar radiation South (W/m²)
1	-7,2	0	0	4,3	0	0	16,4	0	0
2	-7,2	0	0	3,5	0	0	16,4	0	0
3	-6,7	0	0	3,8	0	0	15,4	0	0
4	-7,1	0	0	4,1	0	0	14,7	0	0
5	-7,2	0	0	4,4	6	8	15,3	155	29
6	-7,9	0	0	4,5	54	38	16	118	50
7	-7,4	0	0	5,3	80	94	16,6	108	80
8	-6,8	0	0	5,6	100	158	17,5	86	210
9	-6,7	15	22	6,7	130	476	19	105	379
10	-7,4	44	214	7,9	133	549	19,4	123	529
11	-7,2	79	499	8,6	143	625	20,9	126	662
12	-6,7	76	424	8,7	171	493	22,7	143	691
13	-6,7	69	217	9,7	151	256	23,3	160	604
14	-5,8	55	131	9,9	121	152	23,5	131	641
15	-6,2	41	132	10,9	77	83	23,5	134	484
16	-6,8	15	22	10,7	92	105	24,2	117	315
17	-8	0	0	10,6	68	71	23,6	102	162
18	-8,5	0	0	9,1	64	53	22,6	94	74
19	-8,6	0	0	8,7	38	24	21,5	88	42
20	-8,8	0	0	7,9	2	3	19,6	176	26
21	-8,9	0	0	7,4	0	0	19	0	0
22	-9,7	0	0	6,4	0	0	18,2	0	0
23	-10,7	0	0	6,2	0	0	17,4	0	0
24	-11	0	0	6,4	0	0	16,6	0	0

Winter Stockholm:

Hour	North WINDOW 1 (W·h)	South WINDOW 1 (W·h)	North WINDOW 2 (W·h)	South WINDOW 2 (W·h)
1	-825	-825	-979	-979
2	-825	-825	-979	-979
3	-796	-796	-948	-948
4	-819	-819	-973	-973
5	-825	-825	-979	-979
6	-866	-866	-1024	-1024
7	-837	-837	-992	-992
8	-802	-802	-954	-954
9	-746	-722	-845	-798
10	-689	-118	-692	-19
11	-560	-3	-441	664
12	-541	-1	-429	206
13	-564	-68	-477	61
14	-559	-304	-516	3
15	-629	-324	-636	-16
16	-752	-728	-852	-804
17	-872	-872	-1030	-1030
18	-901	-901	-1062	-1062
19	-906	-906	-1068	-1068
20	-918	-918	-1081	-1081
21	-924	-924	-1087	-1087
22	-970	-970	-1138	-1138
23	-1028	-1028	-1201	-1201
24	-1046	-1046	-1220	-1220
Total heating (W·h/day)	**-19200**	**-16429**	**-21602**	**-18350**

Spring Stockholm:

Hour	North WINDOW 1 (W·h)	South WINDOW 1 (W·h)	North WINDOW 2 (W·h)	South WINDOW 2 (W·h)
1	-328	-328	-421	-421
2	-374	-374	-472	-472
3	-357	-357	-453	-453
4	-339	-339	-434	-434
5	-302	-295	-374	-360
6	-135	-188	-40	-149
7	-1	46	-2	2
8	-4	6	6	-8
9	4	263	6	1804
10	5	629	3	2428
11	8	954	1	3020
12	-4	521	-3	2131
13	-2	-14	-8	620
14	-2	-13	-5	4
15	-3	0	-1	-2
16	-6	-4	-9	4
17	-5	-7	-1	1
18	-5	-12	-2	-5
19	-3	-14	-7	-1
20	-112	-108	-179	-173
21	-148	-148	-225	-225
22	-206	-206	-288	-288
23	-217	-217	-301	-301
24	-206	-206	-288	-288
Total heating (W·h/day)	**-2756**	**-2829**	**-3511**	**-3574**
Total cooling (W·h/day)	**18**	**2373**	**15**	**10010**

Summer Stockholm:

Hour	North WINDOW 1 (W·h)	South WINDOW 1 (W·h)	North WINDOW 2 (W·h)	South WINDOW 2 (W·h)
1	31	31	17	17
2	31	31	8	17
3	31	31	17	17
4	19	19	4	4
5	26	6	352	31
6	9	59	174	35
7	26	33	169	22
8	27	7	114	960
9	81	433	402	2270
10	181	1041	567	3335
11	342	1694	746	4400
12	579	2321	1051	4788
13	696	2479	1231	4258
14	619	2207	1054	4531
15	629	2331	1074	3461
16	642	1874	1032	2382
17	532	1247	867	1276
18	405	633	707	570
19	274	227	550	236
20	379	54	949	20
21	66	52	23	23
22	19	19	36	23
23	34	13	4	30
24	10	37	30	11
Total cooling (W·h/day)	**5686**	**16878**	**11180**	**32718**

Data solar radiation Luleå:

	WINTER-1February			SPRING-1May			SUMMER-1August		
Hour	**Tamb (°C)**	**Global solar radiation North (W/m²)**	**Global solar radiation South (W/m²)**	**Tamb (°C)**	**Global solar radiation North (W/m²)**	**Global solar radiation South (W/m²)**	**Tamb (°C)**	**Global solar radiation North (W/m²)**	**Global solar radiation South (W/m²)**
1	-9,1	0	0	-3,1	0	0	10,7	0	0
2	-8,8	0	0	-3,7	0	0	11	0	0
3	-8,5	0	0	-3,5	0	0	10,7	0	0
4	-8,7	0	0	-3,1	42	12	11,3	146	17
5	-8,3	0	0	-2,6	162	31	11	103	38
6	-8,2	0	0	-2	110	50	11,4	91	59
7	-8,3	0	0	-1,3	73	146	11,9	71	74
8	-7,7	0	0	-0,3	102	277	12,2	95	124
9	-7,6	0	0	1,1	122	540	13	71	76
10	-7,5	29	307	2,4	132	533	14,3	125	201
11	-8,1	41	510	3,6	137	593	15	133	183
12	-8,2	45	586	4,1	136	646	15,5	134	185
13	-8,2	45	514	4,8	124	728	16	147	332
14	-7,9	39	410	5,4	106	648	15,7	144	369
15	-7,9	15	37	5,6	114	443	16,3	116	154
16	-8,2	0	0	6,1	101	188	15,7	108	180
17	-9,1	0	0	6,2	80	128	15,3	35	35
18	-8,9	0	0	5,6	64	48	15,1	45	44
19	-8,8	0	0	5	142	35	14,3	18	19
20	-9	0	0	3,9	46	12	13,7	87	22
21	-9,6	0	0	3,1	0	0	13,4	4	5
22	-10,1	0	0	2,4	0	0	12,8	0	0
23	-10,5	0	0	1,6	0	0	12	0	0
24	-10,7	0	0	0,4	0	0	10,9	0	0

Winter Luleå:

Hour	North WINDOW 1 (W·h)	South WINDOW 1 (W·h)	North WINDOW 2 (W·h)	South WINDOW 2 (W·h)
1	-935	-935	-1100	-1100
2	-918	-918	-1081	-1081
3	-901	-901	-1062	-1062
4	-912	-912	-1074	-1074
5	-889	-889	-1049	-1049
6	-883	-883	-1043	-1043
7	-889	-889	-1049	-1049
8	-854	-854	-1011	-1011
9	-848	-848	-1005	-1005
10	-745	-61	-801	51
11	-740	-94	-757	644
12	-732	-97	-736	1152
13	-732	-34	-736	661
14	-735	-9	-758	-16
15	-815	-742	-921	-771
16	-883	-883	-1043	-1043
17	-935	-935	-1100	-1100
18	-924	-924	-1087	-1087
19	-918	-918	-1081	-1081
20	-930	-930	-1093	-1093
21	-964	-964	-1131	-1131
22	-993	-993	-1163	-1163
23	-1017	-1017	-1188	-1188
24	-1028	-1028	-1201	-1201
Total heating (W·h/day)	**-21122**	**-17659**	**-24267**	**-17838**

Spring Luleå:

Hour	North WINDOW 1 (W·h)	South WINDOW 1 (W·h)	North WINDOW 2 (W·h)	South WINDOW 2 (W·h)
1	-757	-757	-826	-826
2	-792	-792	-864	-864
3	-780	-780	-852	-852
4	-616	-717	-540	-744
5	-184	-624	-13	-583
6	-324	-525	-70	-416
7	-408	-163	-278	30
8	-252	59	-17	54
9	-104	26	18	1649
10	5	24	42	1739
11	5	345	53	2275
12	1	573	80	2689
13	2	919	46	3322
14	5	710	31	2839
15	15	42	32	1463
16	29	72	65	41
17	22	9	23	33
18	-37	-91	7	-11
19	3	-169	34	-138
20	-196	-310	-310	-364
21	-397	-397	-397	-497
22	-438	-438	-438	-541
23	-484	-484	-484	-592
24	-554	-554	-554	-668
Total heating (W·h/day)	**-6321**	**-6802**	**-5644**	**-7098**
Total cooling (W·h/day)	**84**	**2780**	**432**	**16133**

Summer Luleå:

Hour	North WINDOW 1 (W·h)	South WINDOW 1 (W·h)	North WINDOW 2 (W·h)	South WINDOW 2 (W·h)
1	19	19	4	4
2	8	8	23	23
3	19	19	4	4
4	15	24	24	32
5	34	19	84	-1
6	17	26	31	-5
7	8	18	58	2
8	40	9	28	26
9	19	8	9	20
10	28	7	42	561
11	74	1	171	512
12	28	-2	230	578
13	21	542	372	1633
14	31	636	320	1854
15	-3	75	192	451
16	11	2	74	565
17	19	55	8	8
18	43	45	3	6
19	12	31	6	8
20	47	6	0	8
21	-14	19	13	5
22	9	25	11	11
23	2	8	23	23
24	2	2	17	17
Total cooling (W·h/day)	**487**	**1600**	**1749**	**6346**